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FREE AND SEMI-FREE MODEL FLIGHT-TESTING TECHNIQUES USED

IN LOW-SPEED STUDIES OF DYNAMIC STABILITY AND CONTROL

By John P. Campbell 46 refs

NASA Langley Research Center
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By John P. Campbell*

NASA Langley Research Center

SUMMARY

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The various free and semi-free model flight-testing techniques used in low-speed studies of aircraft dynamic stability and control are summarized and discussed. The most appropriate uses for these flying-model techniques and the relative merit of the various techniques for particular applications are indicated.

INTRODUCTION

Flying-model techniques have been used for a variety of dynamic stability and control research applications because of the inherent advantages such techniques have over other means of performing the research. Exploratory flying-model studies can be carried out more safely and economically than full-scale flight tests and can provide much research information which cannot be reliably provided by conventional wind-tunnel investigations or simulator studies. A basic shortcoming of most simulators is that there is usually considerable guesswork involved in determining the correct inputs to the computer. A properly scaled flying model, on the other hand, may be thought of as a simulator with the proper values of the various stability parameters built in for each test condition (assuming, of course, that Reynolds number effects are small).

The emphasis in flying-model investigations has usually been on qualitative rather than quantitative data, for experience has shown that adequate amounts of accurate and consistent quantitative data can be obtained from flying-model tests only at the expense of inordinately large increases in testing time and cost. Model flight testing and conventional wind-tunnel testing have complemented each other with the former supplying the preliminary or exploratory information concerning general flight characteristics (and perhaps even the feasibility of flight) and the latter providing detailed quantitative data on certain aspects of the problem.

A number of variations of the flying-model technique have been developed by researchers to meet particular needs. It is the purpose of this AGARDograph to describe the various techniques which have been used and to indicate the distinguishing features, the advantages and disadvantages, and the areas of application of each.

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*Assistant Chief, Aerospace Mechanics Division.

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The different flying-model techniques can be categorized as follows:

FREE-FLIGHT TECHNIQUES

- WIND TUNNEL
  - Vertical Wind Tunnels
  - Tilting Wind Tunnels
  - Conventional Wind Tunnels
- OUTDOOR
  - Unpowered Models
    - Dropped from helicopter or balloon
    - Catapult launched
  - Powered Models

SEMI-FREE-FLIGHT TECHNIQUES

- Wind tunnel
- Control line
- Track

First, the techniques are grouped into two general categories: free-flight techniques in which the model flies with six degrees of freedom, and semi-free-flight techniques which involve elimination (or, at least, restriction) of one or more of the degrees of freedom. The free-flight techniques are broken down into those which involve testing in wind tunnels and those in which the testing is done either outdoors or in a large building. The wind tunnel techniques are further subdivided into those used in vertical, tilting, or conventional wind tunnels, while the outdoor techniques are subdivided into those involving the use of powered and unpowered models. The semi-free-flight techniques are grouped into three classes: techniques for performing conventional flight with partial restraint in wind tunnels, the control-line techniques in which the model flies in a circle at the end of a tethering line, and the so-called "track" techniques which involve mounting the model on a servo-controlled carriage to effectively provide some degrees of freedom.

The techniques covered in this AGARDograph are limited to those used in low-speed model studies of dynamic stability and control. Thus, high-speed flight techniques such as those utilizing rocket-boosted models outdoors (refs. 1 to 4) and those involving the firing of small models upstream in a high-speed wind tunnel will not be covered. Also omitted from consideration are semi-free-flight-testing techniques used in conducting wind-tunnel studies of flutter characteristics.

MODEL SCALING CONSIDERATIONS

Models used in flight tests must be properly scaled down in mass and moments of inertia, as well as in dimensions, in order to provide dynamic stability and control results that are directly applicable to the corresponding full-scale airplane. Table II presents some of the basic scale factors which apply in the case of models that are dynamically scaled in this manner. Some limitations to the use of dynamic models of this type become apparent from an examination of these scale factors. For example, the dynamic model is tested at Reynolds numbers and Mach numbers considerably less than those of the full-scale airplane at comparable flight conditions. A 1/9-scale dynamic model has a Reynolds number only 1/27 and a Mach number 1/3 that of the corresponding airplane. As for the model motions, the linear velocities are smaller and the angular velocities greater than those of the airplane. A 1/9-scale model has a flight speed only 1/3 that of the airplane but has rolling, yawing, and pitching velocities that are three times as fast as those of the airplane for the same flight conditions.

The discrepancy in Reynolds number between model and full-scale flight is an important factor which often limits the flying-model technique to qualitative, rather than quantitative, studies of stability and control. Experience has indicated that it is not generally feasible to use large enough flying models to avoid scale effects entirely. It has been found, however, that the use of moderate-size models (having an average wing chord greater than about a foot or two) can minimize Reynolds number effects in the normal unstalled flight range. As for representing the stall or other flight conditions involving separated flows which are especially sensitive to scale effect, the flying model is suitable only for qualitative research studies, but it can be a very valuable tool for such studies when used properly. For example, it has been found that although the stall of a small-scale model usually occurs at a lower angle of attack than that for the corresponding airplane, the flight characteristics at the stall are generally quite similar for the model and its full-scale counterpart.

The discrepancy in Mach number between model and full-scale flight is unimportant for low-speed investigations of the type usually carried out with the techniques under consideration. As long as the model speeds remain below a value corresponding to the full-scale speed at which the onset of compressibility effects are evidenced, Mach number can be considered to have a negligible effect on the interpretation of model results in terms of the airplane. For example, if no compressibility effects are expected for a given airplane below a Mach number of 0.70, a 1/9-scale model of the airplane can be tested up to a speed of about 175 miles per hour without requiring corrections for Mach number.

The fact that the angular velocities of the dynamically scaled model are much faster than those of the corresponding airplane does not introduce any uncertainty as to the accuracy of the stability simulation but does pose a problem with regard to the controllability of the model. Because the human pilot has a certain minimum reaction time or response time, there is a fairly definite lower limit to the period of the oscillation which he can control satisfactorily. Reference 5 indicates that this lower limit is reached at an oscillation period of the order of 1 second. Since an oscillation period of 1 second on a 1/9-scale model represents a 3-second period on the airplane, it is apparent that flying models are definitely limited with regard to the range of airplane oscillatory conditions which can be correctly simulated as to controllability. It will be shown later how this inherent controllability simulation problem for small-scale flying models can be partially alleviated by use of the multiple-pilot technique which involves the use of a separate pilot for each of the roll, yaw, and pitch modes of motion.

FREE-FLIGHT TECHNIQUES

Free-flight techniques as defined in this AGARDograph are those in which there is no appreciable restraint of the model under normal flying conditions. Thus, techniques in which there is a slack power and control cable trailing freely from the model in flight are included in this category even though in some cases the cable is pulled taut at times to prevent the model from crashing. Even a freely trailing flexible cable does, of course, provide some degree of restraint, but experience with systems of this type has indicated that the cable effects on stability and control can be kept small enough to be negligible if a special operator is used to maintain the proper amount of slack at all times during the test.

As indicated earlier, the free-flight techniques can be divided into two general types: those used in wind tunnels and those used either outdoors or in a large enclosed test area other than a wind tunnel.

Free-Flight Techniques in Wind Tunnels

A major portion of the free-flight model testing done to date has been carried out in wind tunnels with most of the work being done at the Langley Research Center of the National Aeronautics and Space Administration (NASA) and its predecessor, the National Advisory Committee for Aeronautics (NACA). The techniques used in this research can be logically grouped into three categories, based on the type of wind tunnel in which they are used: (1) techniques used in vertical wind tunnels, (2) techniques used in wind tunnels with a tilting test section, and (3) techniques used in conventional wind tunnels. In general, the first of these techniques has been used primarily in studies of spinning and the other two in flight studies in the normal unstalled angle-of-attack range, but there have been some exceptions which will be pointed out in the following discussion.

Techniques used in vertical wind tunnels.- The first vertical wind tunnels built especially for conducting free-spinning tests of dynamic models were put into operation by the R.A.E. at Farnborough in 1932 (ref. 6) and by the NACA at its Langley Memorial Aeronautical Laboratory in 1935 (ref. 7). The construction of these free-spinning wind tunnels was preceded in both England and the United States by spin research studies in which dynamic scale models were launched in spins from a high platform (refs. 8 and 9).

The R.A.E. spin tunnel was a closed-throat, circular cross-section tunnel having a diameter of 12 feet and a height of 30 feet. A four-bladed fan at the exit originally powered by a 50-horsepower motor provided a maximum test speed of 35 feet per second. Later, the test speed was increased to 56 feet per second by using a 120-horsepower motor and improving the flow conditions in the tunnel.

Fine airspeed adjustment was provided by a Ward-Leonard speed control on the tunnel drive motor. A test model was launched in the tunnel by first letting it rotate in a spinning attitude on a spindle mounted on a retractable arm. When the proper tunnel speed was reached, the model would lift off and the arm would be retracted. Data on the characteristics of the steady spin were obtained by visual observation and motion-picture records. A delayed-action mechanism was used to reverse the controls for attempting recovery from the spin, and a stopwatch was used to determine the time required for recovery. Dynamically scaled models having a span of about 30 inches or less and constructed primarily of balsa were used in the tests.

The first NACA Free-Spinning Tunnel, put into operation in 1935, was generally similar to the R.A.E. tunnel in construction and operating technique. (See ref. 7.) It had a 12-sided test section which measured 15 feet across the flats. Two 130-horsepower motors powered a 16-foot-diameter propeller which provided a top speed of 40 feet per second. The maximum wing span of the models tested in this tunnel was about 36 inches and the maximum model wing loading was approximately 1.3 pounds per square foot. The models were equipped with a clockwork mechanism for moving the aileron, rudder, and elevator surfaces independently and at various time intervals as desired. In the first years of operation of the tunnel, the model was launched from a spindle such as that used in the R.A.E. tunnel. (See fig. 1.) Later, however, the use of the launching spindle was discontinued and the model was merely launched by hand into the airstream with an initial spinning motion. After completion of a test the model was retrieved from the net at the bottom of the test section by means of a clamp on the end of a long pole.

In 1941, the NACA replaced its 15-Foot Free-Spinning Tunnel with a 20-Foot Tunnel, also at Langley. This tunnel is still in active use at the present time under the NASA. The construction features and operation of the tunnel are covered in references 10 and 11. Exterior, interior, and cross-sectional views of this facility are shown in figure 2. The maximum tunnel speed is 97 feet per second and very rapid changes in speed can be obtained by a special speed control on the motor which has a maximum output of about 1300 horsepower. This tunnel is also equipped to provide model control actuation at will instead of by a preset timing device as in earlier tunnels. Copper coils placed around the periphery of the tunnel set up a magnetic field in the tunnel when energized and this magnetic field actuates a magnetic device in the model to operate the controls. Data obtained in tests in this tunnel are primarily in the form of motion-picture records which include records of time and tunnel velocity as well as motions of the model.

The 20-Foot Free-Spinning Tunnel at Langley is also used for research problems other than spinning. For example, the end-over-end tumbling problem of tailless airplanes was studied several years ago and the dynamic stability of various types of spacecraft in vertical descent has been studied during the last few years. One investigation was also conducted in the tunnel with a propeller-powered VTOL model in descending flight by means of a remote-control technique similar to that used in other VTOL flying-model tests at Langley which will be discussed later. In addition, the tunnel has proved useful in determining the dynamic stability characteristics of parachutes, rotors, decelerators, and other vertical-descent-type recovery systems.

Although a major portion of the spin research with free-spinning models to date has been carried out in the three tunnels already covered (R.A.E. Farnborough and the two NACA (NASA) tunnels), a number of other free-spinning tunnels have seen use in various countries. The most interesting development in this area in recent years is the spinning tunnel at the National Aeronautical Establishment, Bedford. (See ref. 12 and fig. 3.)

The N.A.E. tunnel was essentially completed in 1954 when reference 12 was written but it sustained major damage by accident and fire a short time later and is only now being brought into operation after an extended period of renovation. The tunnel has several unique design features intended to increase its research capability over that of earlier tunnels. It is a pressurized tunnel designed for a pressurization to four atmospheres in order to permit the attainment of higher Reynolds numbers. It is equipped with a variable-pitch fan driven by a synchronous electric motor which provides 1500 horsepower for continuous operation and 3000 horsepower for acceleration. Fan blade pitch is varied to provide rapid changes in tunnel velocity up to a maximum of approximately 140 feet per second. The test section is 15 feet in diameter and 30 feet high and netting is installed around the tunnel walls in order to keep the damage to test models to a minimum. For tests carried out under pressurized conditions, a periscope is provided for observation of the model, and launching and retrieval of the model are accomplished by means of a nylon cord suspended from above by a winch and attached to the model a little behind its center of gravity. Actuation of controls for recovery and resetting of the controls for the next test are accomplished by radio control.

Other free-spinning wind tunnels which have been used in spin research include: the University of Lille Tunnel with a test section 2 meters in diameter (refs. 13 and 14); the University of Sydney 3-Foot Tunnel (ref. 15); the U.S. Air Force Vertical Wind Tunnel at Wright-Patterson Air Force Base which has a 12-foot diameter and a top speed of about 140 feet per second; a 15-foot-diameter tunnel in Ottawa; and the composite wind tunnel L-1 (3-meter-diameter vertical jet) of the Training Center for Experimental Aerodynamics at Rhode-Saint-Genese (refs. 16 and 17).

<u>Techniques used in wind tunnels with a tilting test section</u>.- Although there are no wind tunnels with tilting test section presently being used in free-flight model testing, it is considered appropriate to cover in this AGARDograph the early work done by the NACA with this type of tunnel since the technique developed in this work was the forerunner of some of the more advanced flying-model techniques now being used.

In the mid-1930's, Charles H. Zimmerman, who at the time was in charge of the NACA Langley Laboratory's 12-Foot Free-Spinning Tunnel, conceived the idea of the free-flight wind tunnel in which dynamic stability and control tests could be conducted on a small-scale remotely controlled flying model. By 1937 he had completed the development of a small tunnel which served as the pilot model for a larger tunnel to be built later. This small tunnel was a closed-throat, open-return design having a test-section diameter of 5 feet and a length of approximately 6 feet. (See fig. 4.) It was powered by a 5-horsepower electric motor driving a propeller at the rear of the test section. The tunnel drive control provided smooth changes in tunnel speed from 0 to 25 feet per second. The tunnel was mounted on pivots so that its longitudinal axis could be tilted up or down to correspond to the flight-path angle of the flying model. A range of glide-path angles from 0° to 25° could be represented. No provision was made for climb angles since no tests of powered models in this tunnel were contemplated. The models tested in the tunnel were quite small (wing span approximately 2 feet) and a very light construction (balsa shell or balsa framework covered with paper). Small electromagnetic actuators were installed in the model to deflect the control surfaces (fig. 5), and power to operate the actuators was supplied through light flexible wires which trailed freely from the model to the floor of the tunnel.

Two operators were used in conducting tests in the tunnel: one who stood beside the tunnel and controlled the tunnel angle and airspeed, and the other, called the "pilot," who stood behind the test section and flew the model by means of a small control stick which operated electric switches to energize the control actuators in the model. (See fig. 4.) Prior to each flight the model was placed on the floor of the tunnel with the tunnel tilted to an angle slightly higher than that required for equilibrium flight at the predetermined flight condition. Then, when the tunnel airspeed was brought up to a value corresponding to the planned flight speed for this condition, the model would rise from the floor and start flying under the control of the pilot. The tunnel operator continually made adjustments to the tunnel angle and airspeed to keep the model approximately in the center of the tunnel longitudinally and vertically. The information obtained in the tests was qualitative in nature and consisted primarily of ratings for various stability and control characteristics based on observations of the pilot and tunnel operator.

Only a few investigations were carried out in this tunnel but they served to prove that the free-flight technique employed was feasible and warranted further development in a larger tunnel. As a result of this work, a larger and more refined tunnel, the NACA 12-Foot Free-Flight Tunnel was built at the Langley Laboratory and placed in operation in 1939.

A complete description of the NACA 12-Foot Free-Flight Tunnel and its method of operation is presented in reference 18. Photographs of the test section of the tunnel showing a model being prepared for flight and in flight are presented in figures 6 and 7, respectively.

Like the 5-Foot Free-Flight Tunnel, the 12-Foot Free-Flight Tunnel was a simple closed-throat, open-return tunnel mounted on pivots to permit its longitudinal axis to be tilted to correspond to the flight-path angle of the free-flying model. It had a test section of octagonal cross section with the distance between the flat sides of the octagon being 12 feet. The length of the test section was 15 feet and the overall length of the tilting portion of the tunnel was 32 feet. The tunnel was housed in a 60-foot-diameter sphere so that the return passage for the air would be essentially the same for all tunnel angle settings. A range of tunnel angles from 40° glide to 15° climb could be covered and the tunnel airspeed could be varied rapidly and smoothly over a range from 0 to 90 feet per second. In order to minimize damage to the model in crashes, the floor and lower walls of the tunnel were lined with sponge rubber about 2 inches thick.

Three operators were used in the 12-Foot Free-Flight Tunnel. Two of these operators were stationed at the side of the test section to control the tunnel angle and airspeed. In tests of powered models, the tunnel angle operator also controlled the power input to the flying model. The third operator, or "pilot," sat at the bottom rear of the test section and flew the model by operating two small control sticks connected to electrical switches which controlled the power input to small electromagnetic control servos in the model. The power to these servos as well as to the model propeller-drive motor was supplied by a light flexible cable that trailed freely from the model to the tunnel floor.

The operating procedure for this tunnel was essentially the same as that described earlier for the 5-Foot Tunnel. Although the test results obtained were primarily in the form of pilot's opinion regarding the flight characteristics of the model, data were also obtained with motion-picture cameras mounted to photograph the motions of the model in three mutually perpendicular planes. A bank of neon lamps in the common field of the three cameras indicated when the model controls were being used.

The models used in the 12-Foot Free-Flight Tunnel generally had wing spans in the range from 3 to 4 feet and wing loadings from 2 to 4 pounds per square foot. Originally, they were constructed with solid balsa wings and hollow balsa fuselages (ref. 19), but later models had wings of built-up construction with spruce spars and also had fuselages of much stronger construction. In some cases, the fuselage was built with plywood bulkheads supporting either a laminated balsa or fiberglass-plastic shell. In other cases, simplified fuselages for general research models consisted of an aluminum-alloy boom. (See ref. 20.)

The control actuators in the first models tested in the 12-Foot Free-Flight Tunnel were simple spring-centered electromagnetic mechanisms of the type illustrated in reference 18. Later, more powerful pneumatic actuators controlled by solenoid-operated air valves were used. (See ref. 21 and fig. 8.) Both of these actuators provided a "flicker" or "bang-bang" type of control (full on or off) which proved to be more satisfactory than proportional actuators for manual control of the small-scale models. Because of rapid angular motions of these small-scale models, proportional actuators had to be operated so rapidly and to such large deflections that the control was essentially the same as the "bang-bang" type. In some models, rate-sensitive artificial stabilizing devices were used to increase the damping of the angular motion about one or more axes. (See refs. 20 and 21 and fig. 9.) These devices, called roll, yaw, or pitch dampers, consisted of small air-driven rate gyroscopes which, in response to angular velocity, provided a change in signal air pressure to proportional-type pneumatic control actuators that moved the controls of the model to oppose the angular motions. The proportional actuator was usually linked with the "bang-bang" actuator used for manual control so that the outputs of the two actuators were superimposed.

The use of the 12-Foot Free-Flight Tunnel for model flight testing was discontinued in the early 1950's after an improved version of the free-flight technique had been developed for use in the Langley Full-Scale Tunnel. This improved model flight-testing technique is covered in the next section.

Techniques used in conventional wind tunnels.- In 1949, the NACA started the development of a flying-model technique which could be used in exploratory studies of vertical take-off and landing (VTOL) aircraft in the Langley Full-Scale Tunnel. (See ref. 21.) This technique was essentially a refinement of the technique previously developed over a 10-year period in the 12-Foot Free-Flight Tunnel. Within a few years, the technique was also applied to aircraft other than VTOL aircraft, and at that time the Langley Full-Scale Tunnel replaced the 12-Foot Tunnel as the NACA facility for model flight testing. The Full-Scale Tunnel continues to be used in this capacity at the present time under the NASA.

The equipment and technique for flight testing VTOL models in the tunnel is covered in detail in references 21, 22, and 23, while the variations in the technique for testing models other than VTOL models are indicated in references 24 and 25. Some changes in the test setup have been made since these references were published. The sketch presented as figure 10 shows the test setup in its present form.

The Langley Full-Scale Tunnel is well suited to model flight testing because of its large test section (30 feet by 60 feet) and its open-throat design. It has a top speed of about 120 miles per hour but the speed is usually kept below 60 or 70 miles per hour in model flight testing because the roughness of the tunnel flow at the higher speeds makes precise control of the model difficult. One shortcoming of the tunnel for model flight testing is that the speed cannot be changed very rapidly. Thus, for VTOL model tests in the transition from hovering to cruising flight, only very gradual transitions can be simulated.

Since the test section of the Full-Scale Tunnel is not tiltable like that of the 12-Foot Free-Flight Tunnel it superseded, the models must fly in level flight and must therefore be powered. Of course, in VTOL flight tests, powered models are necessary in any event for a proper representation of flight characteristics. In the case of other models which represent either unpowered configurations (such as glide-landing-type reentry vehicles) or configurations in which power effects on stability are small (such as some conventional turbojet-powered airplanes) the thrust required for level flight in the tunnel is supplied by a compressed-air jet exhausted from the rear of the model where the aerodynamic interference effects are negligible. A similar auxiliary compressed-air jet is used in some tests of VTOL models to permit simulation of partial-power descending flight. For example, in such tests with a propeller-powered VTOL model, the power to the propellers is reduced to represent the power condition for a gliding descent, but the model is able to continue flying level in the tunnel by having the thrust of the auxiliary compressed-air jet adjusted to the proper value to compensate for the loss in propeller thrust. Thus, the aerodynamic effects of reduced power to the propellers (and hence reduced slipstream velocity) are represented properly even though the model is acutally in level rather than descending flight.

The sketch of the model flight-testing setup in the Langley Full-Scale Tunnel presented in figure 10 shows some of the innovations introduced into the flight-testing technique when it was transferred from the 12-Foot Free-Flight Tunnel to the Full-Scale Tunnel. Two of the most significant innovations were the overhead safety cable and the multiple-pilot technique.

The overhead safety cable is used to prevent crashes of the model in case of control or power failure or in case the model becomes uncontrollable in some test conditions. The cable consists of braided aircraft cable, 1/16 inch to 1/8 inch in diameter depending on the size and weight of the model being tested. The use of the safety cable is considered essential in testing of this type, for the inevitable crashes which would result if it were not used would cause a several-fold increase in the time and money required to perform a given piece of research. The safety cable attachment system is designed to minimize any effects of the cable on the flight characteristics of the model and also to insure that the slack cable does not become fouled in the propellers of propeller-powered models.

As shown in figure 10, there is a special operator who uses a winch to adjust the safety cable continually during flight to allow sufficient slack for the model to maneuver without restraint. At the same time, this operator must avoid allowing excess slack because of the danger of fouling the propellers or some other portion of the model and he must be alert to pull up the cable quickly to snub the model in event of an emergency. For the first several years of flight testing in the Full-Scale Tunnel, no safety cable winch was installed, and the cable adjustment was accomplished manually by one or two operators.

In addition to the safety cable, wires and plastic tubes are led into the model to supply power for the electric motors and solenoids and compressed air for the pneumatic control actuators, pneumatic motors, and propulsion air jets. In most cases, these wires and tubes are suspended from above as shown in figure 10 and taped to the safety cable from a point about 15 feet above the model down to the model itself. In some tests, the power and control leads have been attached so as to trail downward from the bottom of the model in order to determine whether there has been any significant effect of the overhead arrangement on the flight results. When the wires and plastic tubes are especially bulky and relatively heavy with respect to the model, they can affect the flight characteristics of the model to an appreciable extent. It is necessary, therefore, to keep the sizes of the wires and tubes to a minimum in all cases. When large interference effects are suspected, special care must be taken in the interpretation of the model flight results; and, at times, tests must be made with both the hanging and overhead cable arrangements to establish the seriousness of the interference effects.

The multiple-pilot technique, illustrated in figure 10, involves the use of three pilots - one each for roll, yaw, and pitch control. In addition, three separate operators are used to control the tunnel speed, the power to the model, and the safety cable; and additional operators are used as required to perform such functions as varying wing tilt angle in the case of a propeller tilt-wing VTOL airplane model or wing sweep angle in the case of a variable-sweep airplane model. It is apparent that a high degree of coordination is required in performing tests with this technique.

The three pilots are seated in the most advantageous positions for observing and controlling the model motion with which each is concerned. Although it is possible for a single pilot to fly a model by operating all three controls, such an arrangement is not suitable for research purposes because the pilot must concentrate so intently on the task of keeping the model flying satisfactorily that he is not able to learn much about its stability and control characteristics. This intense concentration is required for several reasons, one of which (the high angular velocities and short oscillation periods of the small-scale models) was indicated earlier in the section "Model Scaling Considerations." In addition to the oscillations being of short period, they are often unstable in the case of VTOL models in hovering flight and this, of course, requires extra concentration on the part of the pilot. Another factor contributing to the difficulty of control is the lack of "feel" in flying a model by remote control. The pilot of a model cannot sense and respond to accelerations in the same manner as the pilot of an airplane but must rely completely on his sense of sight.

In the multiple-pilot technique, each pilot concentrates on only one phase of the motion and can therefore fly the model with greater ease and relaxation. He is, consequently, able to study the stability and controllability associated with his phase of motion more thoroughly and carefully than if he were operating all the controls. Experience has indicated that the use of multiple pilots tends to compensate for the difficulties resulting from higher angular velocities and shorter periods of the models and the lack of "feel" in controlling the models.

For hovering flight, the use of separate pilots for roll, yaw, and pitch control appears to afford no interaction problems because the three controls (and the corresponding motions) are essentially independent of one another, except for the cases in which large engine or propeller gyroscopic moments cause some interaction of the various controls and motions. In forward flight (including the transition from hovering to cruising flight for VTOL models), there is, of course, aerodynamic interaction of the roll and yaw controls and motions, and careful coordination of roll and yaw control is required. In most forward-flight tests, therefore, the roll and yaw controls are electrically interconnected and are operated by a single pilot in the same manner as in the 12-Foot Free-Flight Tunnel described earlier. One of the critical items in performing a transition from hovering to cruising flight with a VTOL model can be the timing of the switch-over from two pilots to one pilot on the roll and yaw controls.

Three basic flight conditions can be studied with flying models in the Full-Scale Tunnel: hovering flight, conventional forward flight, and the transition from hovering to cruising flight. For hovering flight, of course, the tunnel airspeed is zero. Such testing has often been carried out in a large room or in the return passage of the Full-Scale Tunnel instead of in the tunnel test section. (See ref. 21.)

Hovering-flight tests are started with the model either hanging on the safety cable or sitting on its landing gear on the floor. Take-offs are made by increasing the model power until the model rises to the desired height, and then the power is adjusted by the power operator to keep the desired height throughout the flight. The safety cable is allowed to hang slack and, as pointed out previously, the safety-cable operator continually adjusts the cable length during flight to maintain the proper amount of slack. Prior to starting their studies of the stability and control of the model, the pilots establish a steady hovering condition by carefully trimming the controls. Then they perform the desired tests and maneuvers. The pilot who controls the model about the vertical axis in hovering flight must keep the model properly oriented at all times so that the other two pilots have the best view of the model motions with which they are concerned.

Transition tests of VTOL models are started with the model hovering in the test section of the tunnel at zero tunnel airspeed. The tunnel is then started and, as the airspeed increases, the pitch pilot and power operator use their controls to keep the model trimmed longitudinally and to maintain the fore-and-aft position of the model in the test section. Figure 11 shows a 1/8-scale model of the X-18 tilt-wing VTOL airplane in transition flight in the tunnel. These transition flight tests in the Full-Scale Tunnel represent slow constant-altitude transitions since the rate at which the airspeed builds up in this tunnel is relatively slow. For example, it requires at least a minute to make the transition from hovering to conventional forward flight at a model flight speed of about 50 knots. If the model being tested is a 1/9-scale model, this means that the full-scale airplane transition being represented would require over 3 minutes to complete. Since small adjustments or corrections cannot be made readily in tunnel speed, the pitch pilot and power operator must continually make adjustments to keep the model in the center of the test section. In addition to the transitions from hovering to forward flight, the reverse transitions are also performed, and flights are made at various constant speeds for more careful study of any stability and control problems that are encountered in the transition.

In conventional forward-flight tests such as those described in references 24 and 25, a flight is started with the model hanging on its safety cable in the middle of the test section with no thrust being applied. The model is effectively towed by the safety cable in power-off flight as the tunnel airspeed builds up. When the predetermined flying speed of the model is reached, thrust is applied and gradually increased until the flight cable becomes slack and the model is flying freely. Adjustments to elevator setting and thrust are then made if necessary, to trim the model for the particular airspeed. The flight can then be continued to lower or higher airspeeds by changing the elevator trim setting and making the necessary adjustments to tunnel speed and model thrust to maintain equilibrium conditions. As an example of a non-VTOL model in a conventional forward-flight test, figure 12 shows a propeller-powered model of a parawing utility airplane in flight.

Models used for flight testing in the Full-Scale Tunnel have generally been in the weight range from 25 to 80 pounds, with the VTOL models being considerably heavier than non-VTOL models. The models are designed to be true dynamic models (that is, with proper moments of inertia as well as weight) but the construction is much more durable than that of the balsa models used in early Free-Flight Tunnel work. Liberal use is made of fiberglass-plastic, hardwoods, and steel in place of balsa and aluminum. (See refs. 21 and 24.) The control actuators and artificial stabilizing devices used in the models are generally of the pneumatic type described earlier and shown in figure 8. (See ref. 21.) Propeller-type VTOL models have generally been powered with 5- or 10-horsepower variable-frequency electric motors or with vane-type air motors. The air motors have proved to be especially suited to use in flying models because they are much smaller and lighter than electric motors for a given horsepower rating. As much as 6 or 7 horsepower (at an air pressure of about 300 pounds per square inch) is obtained from an air motor weighing only about 1.5 pounds and having a diameter of 3 inches and a length of 3.5 inches. Ducted-fan VTOL models are powered in some cases by these air motors and in other cases by compressed-air tip jets or tip-turbine drive arrangements. Turbojets and turbofans in the flying models are simulated by ducted fans or by compressed-air jets in combination with ejectors. A typical VTOL model, a 1/9-scale model of the XC-142 Tri-Service V/STOL airplane, is shown in figure 13.

The technique for determining low-speed dynamic stability and control characteristics with free-flying models has reached a high degree of development in the NASA Langley Full-Scale Tunnel and has proved to be a very useful and valuable technique. Although highly developed, the technique is still basically simple and is considered primarily as a qualitative rather than quantitative research tool because, as indicated in the Introduction, flying-model techniques are inherently unsuited to providing detailed quantitative data. Results obtained with this technique have been generally in the form of pilot opinion of flight characteristics and motion-picture records obtained with 16-millimeter cameras located at three or four different positions around the test section.

A flying-model technique somewhat similar to that used in the Langley Full-Scale Tunnel was used in one investigation conducted in the NASA Ames Research Center 40- by 80-Foot Tunnel in the mid-1950's on a model of the Lockheed XFV-1 VTOL airplane. The model was much larger, more complex, and more expensive than the VTOL models tested in the Langley Full-Scale Tunnel and also required a special tethering arrangement. A single pilot was used to fly the model but he required the assistance of automatic stabilization equipment to make successful flights. This work was discontinued after only one flight investigation, partly because the techniques and equipment used appeared to be less satisfactory than the much simpler and less expensive techniques and equipment used in the Langley Full-Scale Tunnel.

Outdoor Free-Flight Techniques

The free-flight techniques which have been used outdoors (or in a large building) can be grouped into two general categories based on whether they make use of powered or unpowered models. The techniques making use of unpowered models can be subdivided further into those in which the model is dropped from a helicopter or balloon and those which are catapult-launched. Techniques involving the use of rocket-boosted models will not be covered since such techniques are used primarily for high-speed testing and, in any event, have been employed so extensively that their inclusion would mean a major extension in the scope of the AGARDograph.

Techniques using unpowered models dropped from helicopter or balloon.- Considerable research has been performed at the NASA Langley Research Center with radio-controlled models dropped from a helicopter and this technique is still in active use. (See refs. 26 and 27.) A limited amount of research was also carried out by the Air Force with this technique several years ago but this work was discontinued. In one of the Air Force studies the model was dropped from a blimp instead of a helicopter. In England, the R.A.E. has done some work with simplified models (without radio control) dropped from a balloon or a helicopter (ref. 28), but only a few studies have been made to date with this technique. The following discussion will deal primarily with the techniques being used by the NASA and the R.A.E.

The NASA technique utilizing radio-controlled models dropped from a helicopter has been in use for several years and has reached a fairly advanced state of development. A complete description of the technique and associated equipment is presented in reference 26. Although this technique was developed primarily to study the incipient- and developed-spin characteristics of airplanes, it has also been used for other research such as studies of the flight characteristics of aircraft and reentry vehicles (ref. 27) and studies of deployment and flight characteristics of various types of recovery systems. The basic advantages of this technique over the Free-Spinning Tunnel for spin research are the better simulation of spin-entry conditions (spin can be entered from stall) and the provision for using larger, heavier models (which permits an increase in Reynolds number in cases where scale effects are very important).

In the NASA radio-control technique, the models are dropped from a special launching rig mounted on a helicopter (fig. 14) and controlled from ground stations, usually by two pilots. When the model has descended from the drop altitude (usually about 3,000 or 3,500 feet) to an altitude of about 500 feet, a recovery parachute is deployed to effect a safe landing. The ground control stations consist of two tracking units which are modified power-driven gun trailer mounts (fig. 15). Each tracking unit has stations (equipped with binoculars) for a pilot and observer (in addition to the tracking operator) and is also equipped with a movie camera having a telephoto lens. For best observation and control of gliding models, one of the tracking units (for the longitudinal-control pilot) is placed beside the planned flight path of the model and the other unit (for the lateral-control pilot) is placed on the ground track of the helicopter so that the pilot will be a few hundred feet behind the model when it is launched. (See ref. 26.) In some cases, for spin research studies, the two tracking units have been placed together well to one side of the planned flight path. In addition to the cameras on the tracking units, a third movie camera is installed in the helicopter for an aerial view of the model.

The models used by the NASA in the radio-control drop tests are constructed primarily of fiberglass cloth and plastic, with the fuselages being a 1/4-inch-thick hollow shell and the wings and tail surfaces having solid balsa cores. The model weights have varied from about 25 to 200 pounds, with the heavier models being ballasted to represent airplanes flying at altitudes of about 30,000 feet. The largest model tested to date had a length of 8 feet and a wing span of 6 feet. Radio receivers and electric-motor-powered control actuators are installed in the model to provide simultaneous operation of all control surfaces and to release the recovery parachute. Both the bang-bang (full on or off) and trim-type controls have been used. Data recording in the model is accomplished photographically by an electrically driven 16-millimeter movie camera which photographs the view of the horizon as seen from the pilot's cockpit and also records the positions of flow-direction and airspeed-indicator vanes (mounted on a nose boom), control-position indicators, and a timing light. In addition, magnetic tape recorders on the ground are used to record control signals and voice communications between the helicopter and ground control stations.

The model launching rig installed on the side of the helicopter (fig. 14) can be lowered to a position below the helicopter for launching in order to minimize the interference of the helicopter on the model. The rig is designed so that models can either be held stationary for gliding flight launches (with the helicopter flying forward) or be prerotated for spin-test launches (with the helicopter hovering).

The R.A.E. drop-model technique described in reference 28 differs from the NASA technique in a number of respects. The models used were simple research models having a minimum of instrumentation and no provisions for radio control. Reference 28 indicates, however, that in future use of the technique, improved model instrumentation and some limited form of radio control will be incorporated. The models were not fitted with recovery parachutes and were therefore considered expendable. Model construction was of fiberglass-reinforced plastics as described in reference 29. In the first tests, the models were launched by hand from a captive balloon flying at altitude of about 1,500 feet. Later, the launching technique consisted of suspending the model below the helicopter at the end of a 150-foot-long weighted cable and then releasing the model in forward flight at approximately its trimmed speed. Records of airspeed, glide-path angle, and model attitude were obtained from a kinetheodolite and a high-speed movie camera on the ground. Pitch-response measurements were obtained from two normal accelerometers mounted on the longitudinal axis of the model. The elevator was controlled by a clockwork mechanism which applied elevator pulses at regular intervals and in some cases also trimmed the surface gradually upward to vary the speed during flight. In addition to the measurements of elevator response obtained from the accelerometers, measurements of the damping of the lateral oscillation (Dutch roll) were obtained from the movie records.

Techniques using catapulted unpowered models.- Mention was made in an earlier section of the use of catapulted unpowered models in early spin research studies in both England and the United States. (See refs. 8 and 9.) These studies were not very extensive and were discontinued after the free-spinning wind tunnels were put into operation. In the 1930's, the NACA developed a technique for gust-loads research which involved the use of catapult-launched free-flying models flying through the open throat of a vertical wind tunnel (ref. 30). Later, in the 1940's this technique was refined and the equipment improved in a new facility - the Langley Gust Tunnel - which was designed to test models with wing spans up to 6 feet at forward speeds up to 100 miles per hour and at gust velocities up to 20 feet per second. (See ref. 31.) Since this technique was used for gust-loads studies rather than dynamic stability and control research, it will not be covered further in this AGARDograph. Other research with catapulted dynamic models which falls outside the scope of this paper includes the work done at Langley Research Center on the water-landing characteristics of "ditched" airplanes and on the landing characteristics (on water and other surfaces) of various spacecraft configurations.

In the 1950's, the Langley Laboratory of the NACA started using unpowered, catapult-launched models for studies of the stall and incipient spin. (See ref. 32.) Initially, in this work small balsa models were tested in a building about 70 feet square by 60 feet high. The launching apparatus, which was located near one wall of the building about 55 feet above the floor, consisted of an elastic cord which propelled a launching platform along a short track. The model was launched at a speed slightly in excess of the stalling speed and at an angle of attack slightly below the stall angle. The elevator control was preset to a position which would cause the model to pitch up through the stall and, in some cases, the rudder was preset to initiate a yawing motion and thereby precipitate a roll-off at the stall. In order to minimize damage to the model, a large retrieval net was hung above the floor and up the wall opposite the catapult. Although this work did indicate promise for a technique utilizing catapult-launched models, the particular setup described in reference 32 was not considered satisfactory because of space limitations. Later, this objection was overcome in some tests made by the NASA in a Navy airship hangar. In these tests the catapult was located 137 feet above the floor and there was ample room to accommodate all possible model flight paths. Models up to about 5 pounds in weight could be launched at speeds up to about 50 feet per second, and the model control surfaces were operated in flight by radio control. Data were obtained from film records provided by two synchronized ballistic-type cameras and two 16-millimeter movie cameras.

Techniques using powered models.- Only a very limited amount of research has been conducted with radio-controlled powered models. In the 1950's, the San Diego Division of Consolidated Vultee Aircraft Corporation developed a technique for testing radio-controlled dynamically scaled models of seaplanes, but this work was directed primarily toward studies of hydrodynamic rather than aerodynamic characteristics.

The NASA Langley Research Center, which has done extensive work with the radio-controlled drop model technique as indicated earlier, has also conducted some flight investigations with powered radio-controlled models. Reference 33 covers one investigation of this type in which a propeller-powered airplane model equipped with a parawing was flown. (See fig. 16.) The model, which weighed 15.5 pounds and was powered by a 1-horsepower motor, was taken off from the ground and was controlled by conventional elevator and rudder surfaces. This technique for testing powered radio-controlled models is a very simple one and is essentially the same as that used by model airplane hobbyists. It has been used in a number of instances where exploratory flight studies of some new feature were desired without resorting to the use of elaborate test equipment. For example, Lockheed Aircraft Corporation made good use of this technique with some early flying-model studies of their nonarticulated rotor helicopter.

SEMI-FREE-FLIGHT TECHNIQUES

As indicated in the Introduction, the semi-free-flight techniques can be grouped into three general classes: techniques for performing conventional flight with partial restraint in wind tunnels, the control-line techniques in which the model flies in a circle at the end of a tethering line, and the so-called "track" techniques in which the model is mounted on a servo-controlled carriage to effectively provide some degrees of freedom.

Techniques using partially restrained models in wind tunnels.- Most of the work with partially restrained flying models in wind tunnels has been done by ONERA in its large open-throat S1Ch tunnel at Chalais-Meudon in Paris. (See refs. 34 to 38.) The schematic sketches in figure 17 show two different funicular suspension systems which have been used in this testing technique. An overhead cable system with counterweights is used to support a portion of the model weight and a longitudinal towline is used to supplement the thrust of powered models (or to replace the thrust in the case of unpowered models). In the system without servo controls (fig. 17(a)), both the overhead cable and the towline are attached to the model by means of bridles attached to points on the wings that lie on a line passing through the center of gravity and perpendicular to the plane of symmetry. In some cases, there are also two slack lines leading off laterally from these wing attachment points which can be controlled manually to snub the model in case something goes wrong. In the servo-controlled system (fig. 17(b)), no bridles are used but the vertical and longitudinal cables are servo controlled so that they remain essentially perpendicular and parallel to the airstream, respectively. Thus, there are four degrees of freedom: three degrees of rotational freedom and freedom of lateral translation.

The models are equipped with control actuators that are operated by two pilots located in a control room at the side of the test section. One of the pilots controls the longitudinal motion while directly observing the model. The second pilot controls the model laterally by observing it on a television screen. The television camera which provides this view is located at the rear of the test section. Records of model motions and control deflections are obtained by photographing instruments mounted in the model, and motion-picture records of the model in flight are also obtained. Models of the Breguet 940 and 941 propeller-powered STOL aircraft tested in the tunnel using this technique (fig. 18) were powered with variable-frequency electric motors and weighed about 125 pounds. In one investigation in the Chalais-Meudon S1Ch tunnel involving this technique, the Deltaviex experimental airplane with a 70° swept wing and a jet flap was tested with a pilot in the cockpit to study low-speed stability and control of the airplane. (See ref. 36.)

Although the system of cable restraints used in this technique does produce flight characteristics that are not directly applicable to a completely free-flying aircraft, the research group at ONERA conducting the tests has found that reliable information can be obtained by careful analysis and interpretation of the results.

Control-line techniques.- Control-line techniques are considered to be those in which a model is flown in circling flight at the end of a tethering line (or, in some cases, at the end of a pivoted boom). Model hobbyists have used such a technique (sometimes called U-control) for many years in sport flying of small models powered by minature powerplants. Control-line techniques are classed as semi-free techniques because the models are restrained in roll and yaw attitude and lateral displacement but experience only minor restraints in pitch attitude and vertical or fore-and-aft displacement.

Research use was first made of the control-line technique at the Wright Field research establishment of the U.S. Air Force in the late 1940's and early 1950's. (See ref. 39.) After preliminary work with a fairly small control-line arrangement, a 150-foot radius paved flying circle was constructed at Wright Field. In this larger setup, the pilot of the model sat outside the flying circle and operated the model controls remotely through a mechanical linkage system that extended from his control station to the center post to which the tethering lines were attached. Only a very limited amount of work was done with this facility before its operation was discontinued.

The most extensive research with the control-line technique to date has been carried out by the NASA Langley Research Center on its Control-Line Facility. (See refs. 21, 40, and 41.) This facility, a sketch of which is presented in figure 19, was put into operation in 1955 primarily for the purpose of increasing the research capability with free-flying VTOL models. Very rapid transitions from hovering to forward flight can be made with this facility, whereas transitions performed in the Langley Full-Scale Tunnel are necessarily very slow, as pointed out earlier.

The Langley Control-Line Facility shown in figure 19 consists essentially of a standard crane with its circular track mounted on concrete pillars. The crane is placed in the center of a 130-foot-diameter concrete circle which is located in a wooded area that serves as a windbreak and permits testing even when it is fairly windy outside the woods. In order to provide control stations for the four operators of the facility, the standard cab on the right side of the crane was enlarged and a duplicate cab was added to the left side of the crane. The crane, which has a standard 4-speed transmission, can be rotated at speeds up to 20 revolutions per minute, and even when in high gear can accelerate from a standing start to top speed in approximately one-fourth of a revolution. In addition to having this excellent acceleration, the crane can also be rotated smoothly and accurately enough to follow VTOL models closely in rapid transitions.

The arrangement of the overhead safety cable and the power and control cable is the same as that used in the Langley Full-Scale Tunnel free-flying model technique. In this case, the support for the overhead cable is provided by a special jib attached to the vertical boom. The point of attachment of the overhead cable at the end of the jib is about 30 feet above the ground and 50 feet from the center of rotation of the crane. The safety cable is led through the jib and down the boom to the safety-cable operator in the cab of the crane.

The control lines run from an attachment on the left side of the model at the fore-and-aft location of the center of gravity to attachments on the vertical boom about 15 feet above the ground. In the original setup, differential movement of the two control lines was used to vary the position of the elevator (or other longitudinal control) of the model. This control system did not prove to be entirely satisfactory for flying VTOL models because, in hovering flight, the control lines occasionally slackened momentarily and caused the control of the model to become erratic. This difficulty was eliminated in a revised longitudinal control system which provided for the installation in the models of control actuators and trim motors identical to those used in the free-flying models tested in the Langley Full-Scale Tunnel.

In forward flight on the Control-Line Facility, the centrifugal force on the flying model keeps the restraining line taut. In order to keep the line taut in hovering flight (when there is no centrifugal force) VTOL models are flown with the resultant thrust vector tilted slightly outward away from the center of the circle. In some cases, an additional outward force is provided by an inwardly directed compressed-air jet at the center of the gravity of the model. The restraining line is attached to the boom by a device which automatically keeps the line horizontal regardless of the height at which the model is flying. This device consists of a vertical track installed on the boom and a small motor-driven carriage to which the restraining line is attached. When the restraining line is not horizontal, it operates a switch to an electric motor which runs the carriage up or down the track to make the line horizontal again. In this system a small amount of dead spot was used to prevent the carriage from overshooting and "hunting." The purpose of this device is to minimize the effective static stability of height which results from centrifugal force. That is, with a fixed attachment point of the restraining line on the boom, the centrifugal force acting on the model tends to make it fly at the same height as the attachment point. With this device, which automatically keeps the restraining line horizontal, models can be taken off the ground and flown at any height up to approximately 30 feet without experiencing an appreciable effect of this type.

Before a transition test is started on the Control-Line Facility, a VTOL model takes off vertically and is trimmed for steady hovering flight. Then the pitch pilot operates the model controls to perform the transition to forward flight at any desired rate while the power operator adjusts the model power to maintain the desired altitude (usually about 15 feet above the ground). The crane operator rotates the crane so that the end of the jib is above the model at all times. It should be emphasized that the model flies at whatever speeds are called for by the control movements made by the pitch pilot. The crane merely follows the model so that the crane rotation has virtually no effect on the model motions. In order to complete the transition tests, the reverse transition from forward flight to hovering is made and the model then lands.

Test data on the Control-Line Facility are obtained in the form of motion-picture records obtained with a 16-millimeter camera mounted on top of the cab of the crane and photographing the motions of the model. Also included in the field of view of the camera are indicators of model velocity and control position.

Control-line models have generally had the same types of propulsion systems as those tested in the Full-Scale Tunnel, but some turbojet-type VTOL models flown on the Control-Line Facility have been powered by hydrogen-peroxide rocket motors. (See ref. 21 and fig. 20.)

The Control-Line Facility has been used in a number of investigations of the characteristics of VTOL airplane models during rapid transitions from hovering to cruising flight and back to hovering. It has been especially valuable for studying very rapid landing transitions in which a pronounced flare is made in order to stop quickly. (See refs. 40 and 41.) In addition, the facility has been used to study the short takeoff and landing (STOL) characteristics of VTOL airplane models.

Adaptations of the control-line technique for dynamic stability and response research on models of ground-cushion or ground-effect machines have been made by the U.S. Navy at its David Taylor Model Basin (ref. 42) and by the Institute of Aerophysics at the University of Toronto (ref. 43). The setups described in these references were not intended to be permanent facilities but were merely temporary test setups for a few research studies.

A photograph of the circular test track and model setup for tests of a 7-foot GEM (ground effect machine) at David Taylor Model Basin is shown in figure 21. The track, which has an outside diameter of 46 feet, is level concrete around 270° of the circle but has a sinusoidal wave construction over the remaining 90° for determining the response of a free-flying GEM model to surface roughness. The waved surface is of temporary construction, consisting of wet sand shaped to the desired contour and sprinkled with cement powder to provide a thin but serviceable crust. Rapid changes in the configuration of this test segment can be made by raking off the crust and building up a new shape. Compressed air to provide the ground cushion for the test vehicle is supplied through the center pylon and thence through flexible plastic tubes which connect to a manifold on the vehicle. The main restraining member of the setup is a light aluminum tube attached to the center pylon by a self-alining ball bearing and to the vehicle by a truss arrangement. Test records are obtained by means of a 35-millimeter high-speed movie camera attached to the top of the center pylon as shown in figure 21. Model test height is controlled by regulating the compressed-air supply and the test speed can be varied by changing the deflection of control vanes in the side portions of the peripheral nozzle. Because of the success obtained with this track setup, David Taylor Model Basin is now constructing a larger (80-foot diameter) and more permanent facility of this type for future GEM research.

The GEM control-line setup used at the Institute of Aerophysics (ref. 43) was much smaller than the one at David Taylor Model Basin. The track in this case consisted of an annular plywood table having a radius of 9 feet from the center of the track to the center post. The tethering lines connecting the model to the movable portion of the center post consisted of light steel wires which could be moved differentially to operate the elevator control surface of the model. A motion-picture camera mounted above the center post and pointed directly downward photographed the model motions through a mirror mounted at an angle of about 45° on the movable portion of the center post.

Track techniques.- The only example to date of a successful application of the track technique to semi-free flight testing of dynamic models is the Princeton University Free-Flight Facility. (See refs. 44 to 46.) This unique facility, which was developed primarily for the testing of VTOL models in hovering and low-speed flight, involves the use of a servo-controlled carriage which runs along a straight horizontal track 750 feet long. (See fig. 22.) Mounted on this horizontally moving carriage is a vertical track on which runs a vertically moving servo-controlled carriage with the model support boom installed. The model is attached to this boom with angular freedom in pitch and also with ±9 inches of fore-and-aft freedom along a horizontal track (as shown by the closeup view presented in fig. 23) and ±3 inches of vertical freedom.

During a test, the propulsion system of the model provides the lift to support the model weight and the thrust to overcome the model drag in forward flight. The model support strut is moved horizontally and vertically by the two servo-controlled carriages in response to signals from position indicators at the model so that the model stays in the center of its small range of horizontal and vertical freedom. The model support strut therefore provides no restraint to the model in the horizontal or vertical direction (unless, of course, it reaches one end of its rather limited range of freedom in the horizontal or vertical direction). Extensive work was required to develop a system which would respond rapidly and accurately enough to keep the model motions from being affected to an unsatisfactory extent by the support boom. Since the model is restrained in lateral displacement and in bank and yaw attitude, it has the same limitation as the Control-Line Facility in permitting only studies of longitudinal characteristics. (It is possible to study lateral characteristics in hovering flight with either of these two facilities, however, by making tests with the model turned 90° about its vertical axis.)

The Princeton Track Facility is housed in a building 760 feet long with a cross section measuring 30 feet by 30 feet. Models can be tested up to speeds of 40 feet per second with a maximum acceleration of 0.6g. The helicopter and VTOL models tested to date have weighed about 25 pounds but models weighing as much as 40 pounds can be tested. Unlike the models tested on the Control-Line Facility, the models tested on the Princeton track are not equipped with controls for flying, so the flight data obtained are limited to longitudinal stability information and response to pulse disturbances. The data are transmitted from the model to the recording equipment by telemetering. Experience to date with this facility reported in references 45 and 46 has indicated good correlation between the dynamic longitudinal stability characteristics measured for models and the corresponding full-scale aircraft.

CONCLUDING REMARKS

In this discussion of free and semi-free model flight-testing techniques, an effort has been made to indicate the most appropriate uses for the different techniques and their relative merit for particular applications. In general, these techniques have been applied most advantageously to research problems when qualitative rather than accurate quantitative data have been required. The flying-model techniques have proved to be especially valuable in exploratory studies of new aircraft configurations or abnormal flight conditions. It has appeared highly desirable to keep the techniques (including the associated equipment and models) as simple as possible to perform the required research because experience has indicated that improvements in results obtained with highly refined and complicated equipment do not usually justify the accompanying increases in development costs and operating costs.

In view of certain inherent advantages of the free and semi-free model flight-testing techniques over full-scale flight testing, conventional wind-tunnel testing, and simulator studies and in view of the number of successful applications of the flying-model techniques made to date, it is appropriate to conclude that these techniques are now firmly established as research tools and offer promise of continued value in future research on the dynamic stability and control characteristics of aircraft.

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TABLE I.- REFERENCES COVERING VARIOUS TECHNIQUES

Free-Flight Techniques:	
Wind tunnel:	
Vertical wind tunnels	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
Tilting wind tunnels	18, 19, 20
Conventional wind tunnels	21, 22, 23, 24, 25
Outdoor:	
Unpowered models:	
Dropped from helicopter or balloon	26, 27, 28, 29
Catapult launched	30, 31, 32
Powered models	33
Semi-Free-Flight Techniques:	
Wind tunnel	34, 35, 36, 37, 38
Control line	21, 39, 40, 41, 42, 43
Track	44, 45, 46

TABLE II.- SCALE FACTORS FOR DYNAMIC MODELS

[Model values are obtained by multiplying airplane values by the following scale factors where N is the model-to-airplane scale ratio]

	Scale factor
Linear dimension	N
Area	N^2
Volume, weight, mass, force	N^3
Moment	N^4
Moment of inertia	N^5
Linear velocity	$N^{0.5}$
Linear acceleration	1
Angular velocity	$N^{-0.5}$
Angular acceleration	N^{-1}
Power	$N^{3.5}$
Time	$N^{0.5}$
Frequency	$N^{-0.5}$
Wing loading, disk loading	N
Reynolds number	$N^{1.5}$
Mach number	$N^{0.5}$

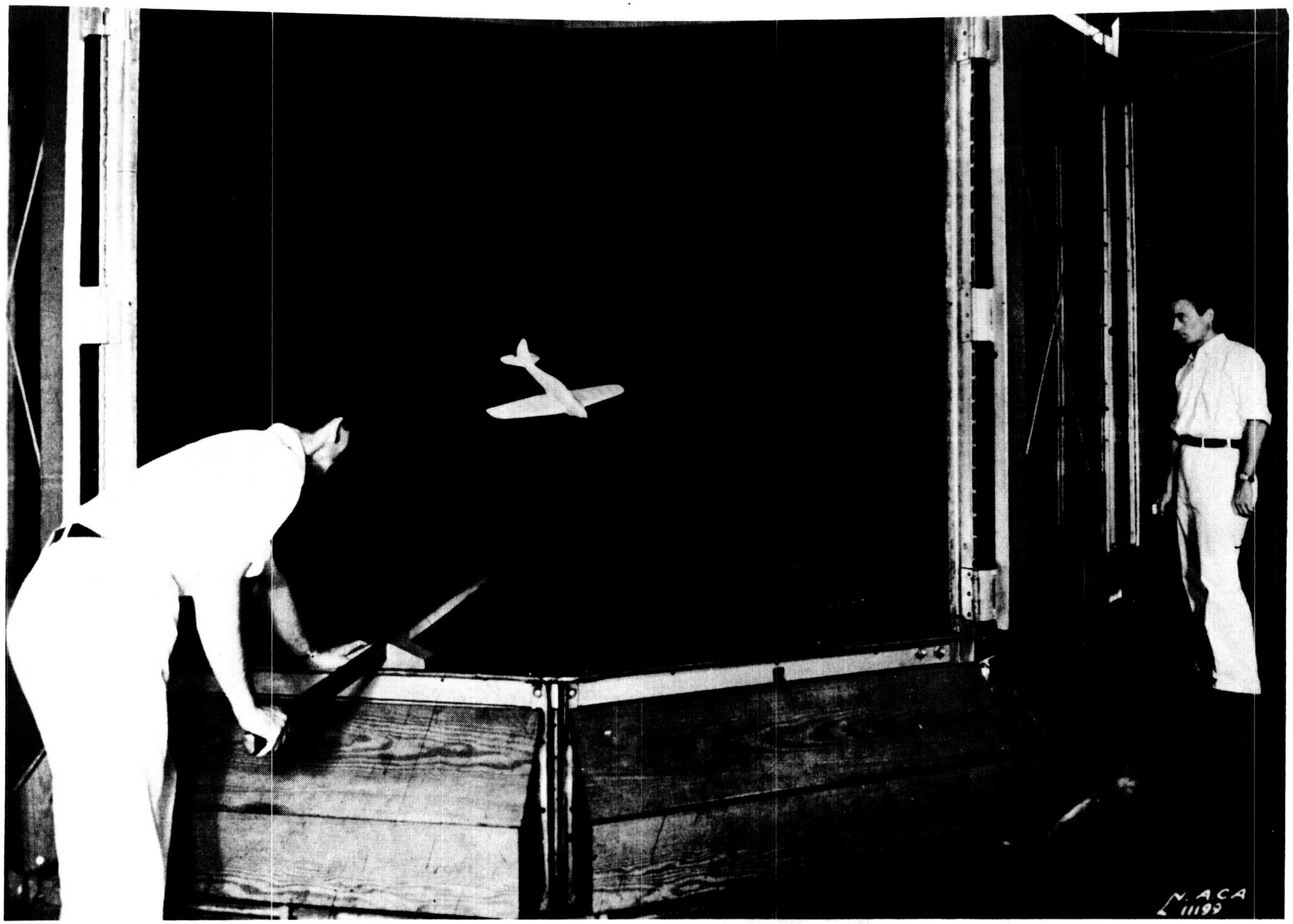

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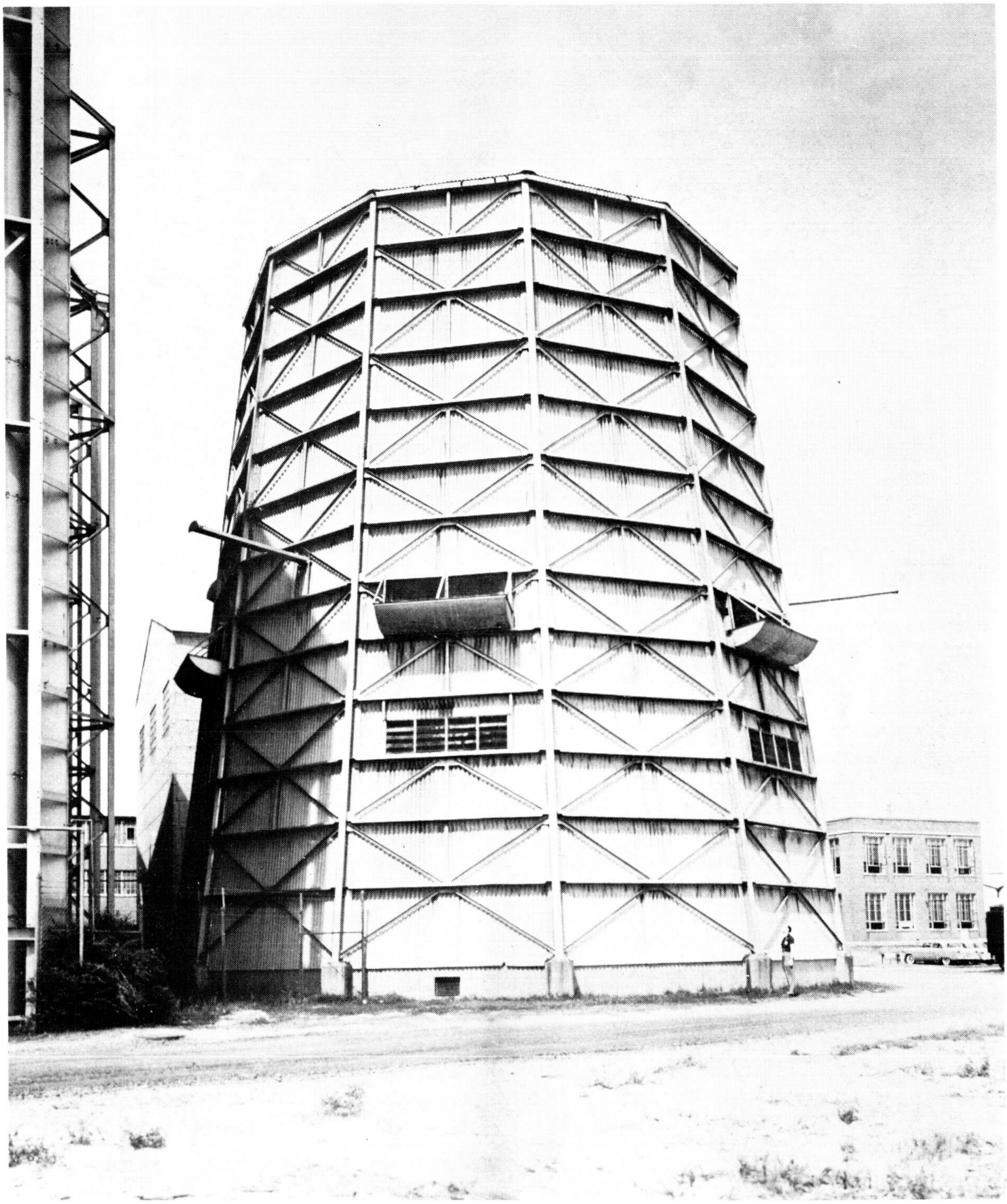
Figure 1.- NACA Langley 15-Foot Spin Tunnel showing model being launched into vertical air-stream by means of launching spindle.



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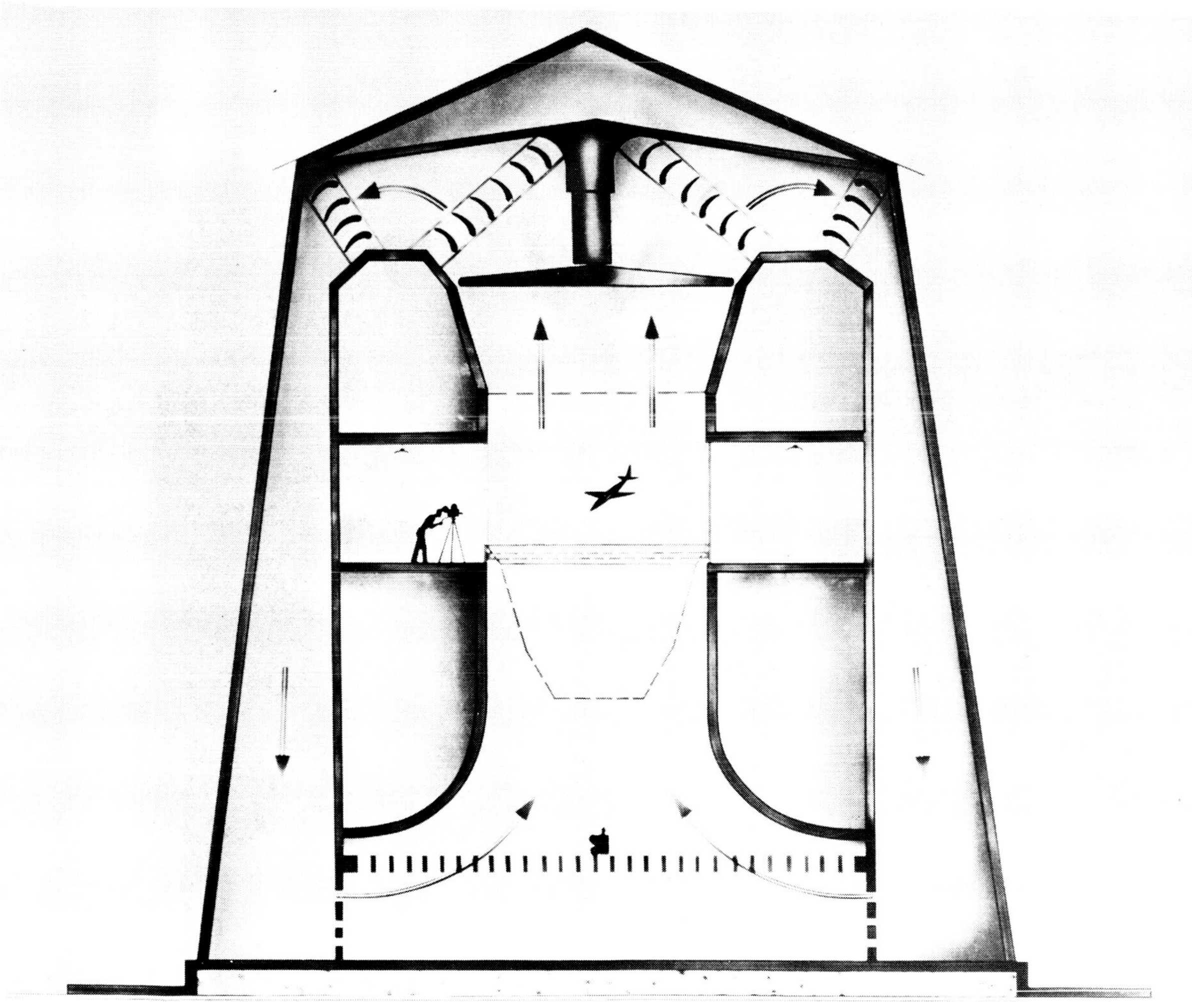
L-86257

(a) Exterior view.

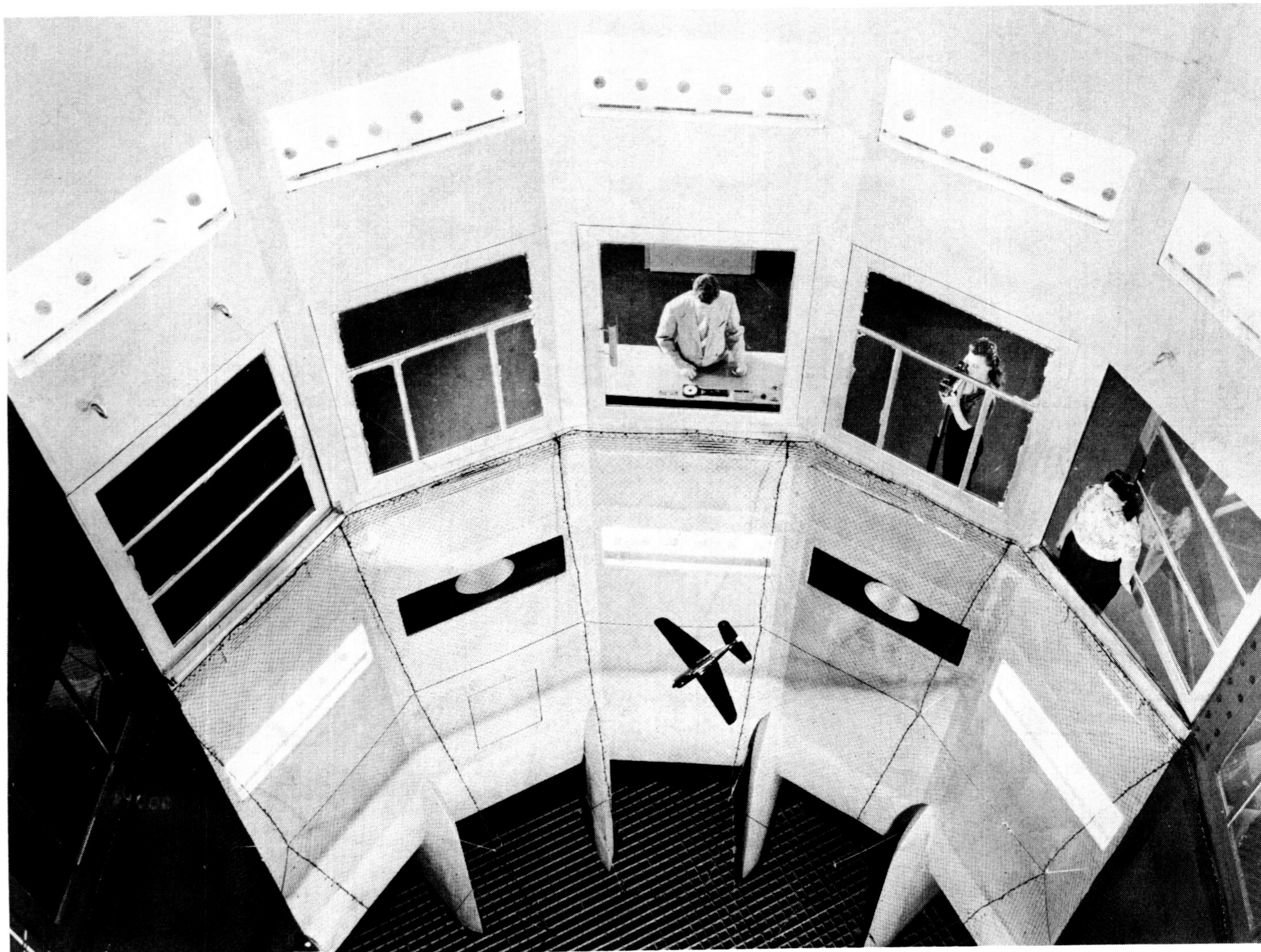
Figure 2.- NASA Langley 20-Foot Free-Spinning Tunnel.



(b) Cross-sectional view.

NACA
L-86258

Figure 2.- Continued.



NACA
L-49000

(c) Interior view.

Figure 2.- Concluded.

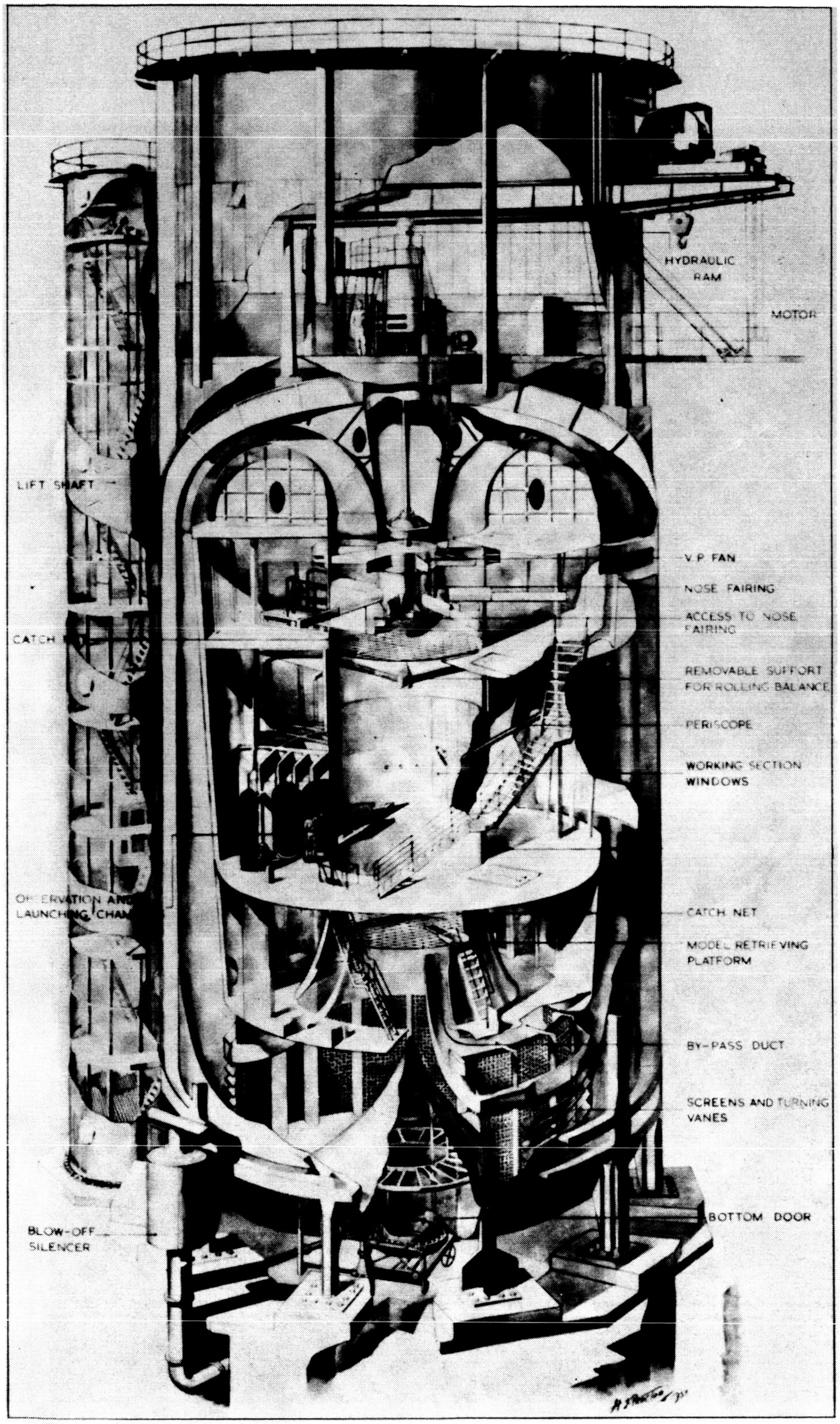


Figure 3.- Cross-sectional view of Free-Spinning Tunnel at the National Aeronautical Establishment, Bedford.

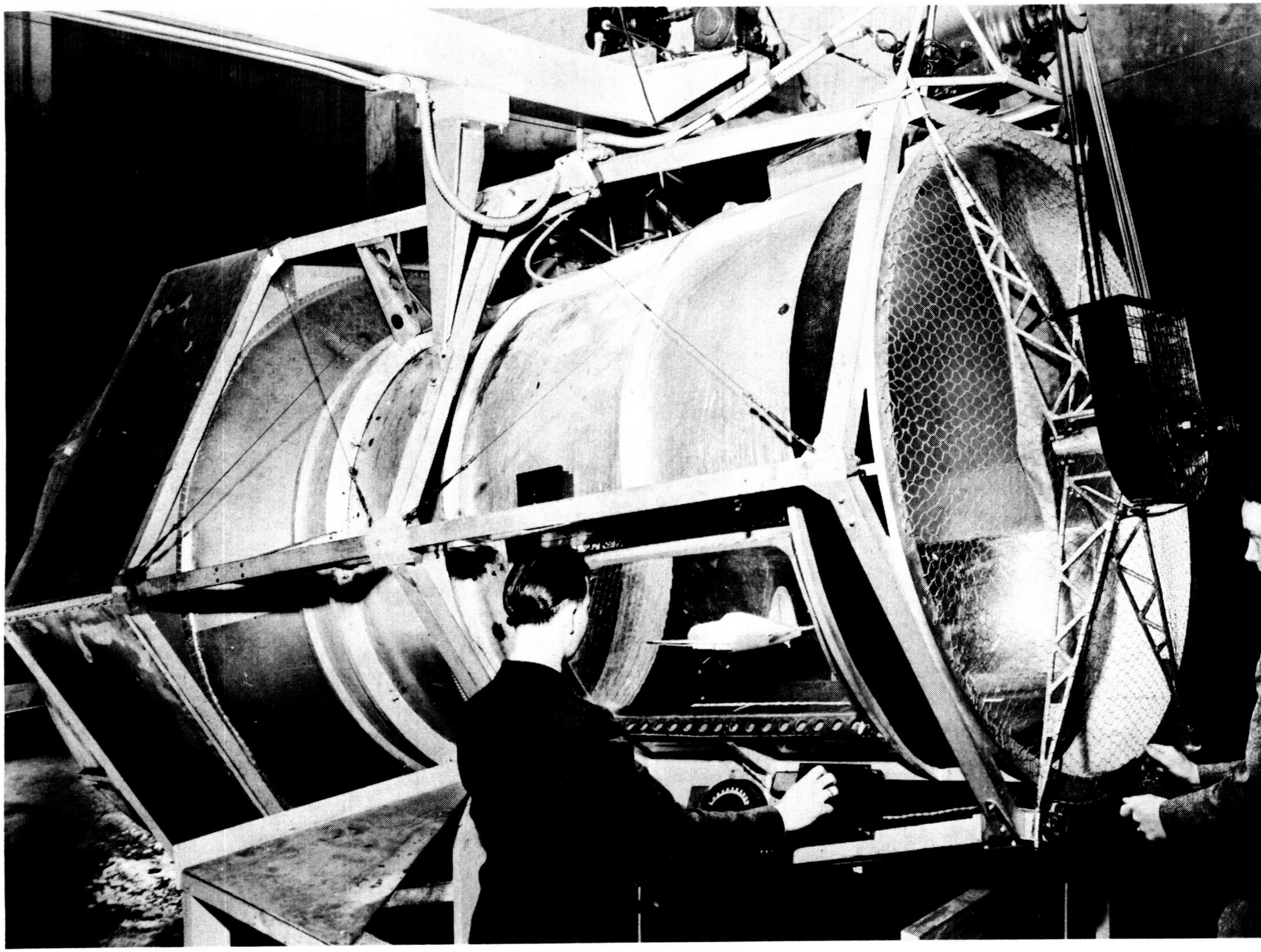


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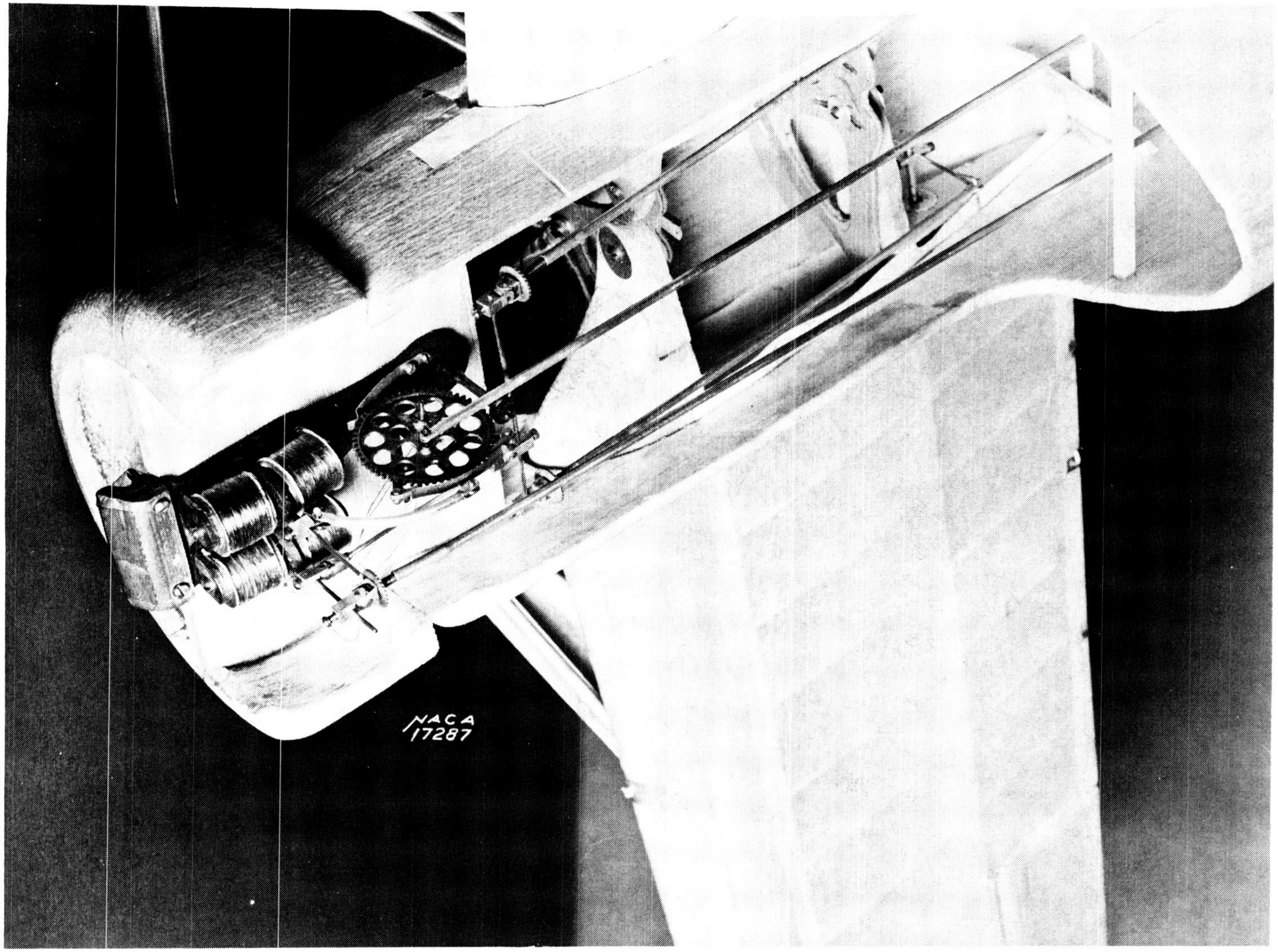
Figure 4.- NACA Langley 5-Foot Free-Flight Tunnel.



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L-17287

Figure 5.- Close-up view of control actuators in model tested in 5-Foot Free-Flight Tunnel.

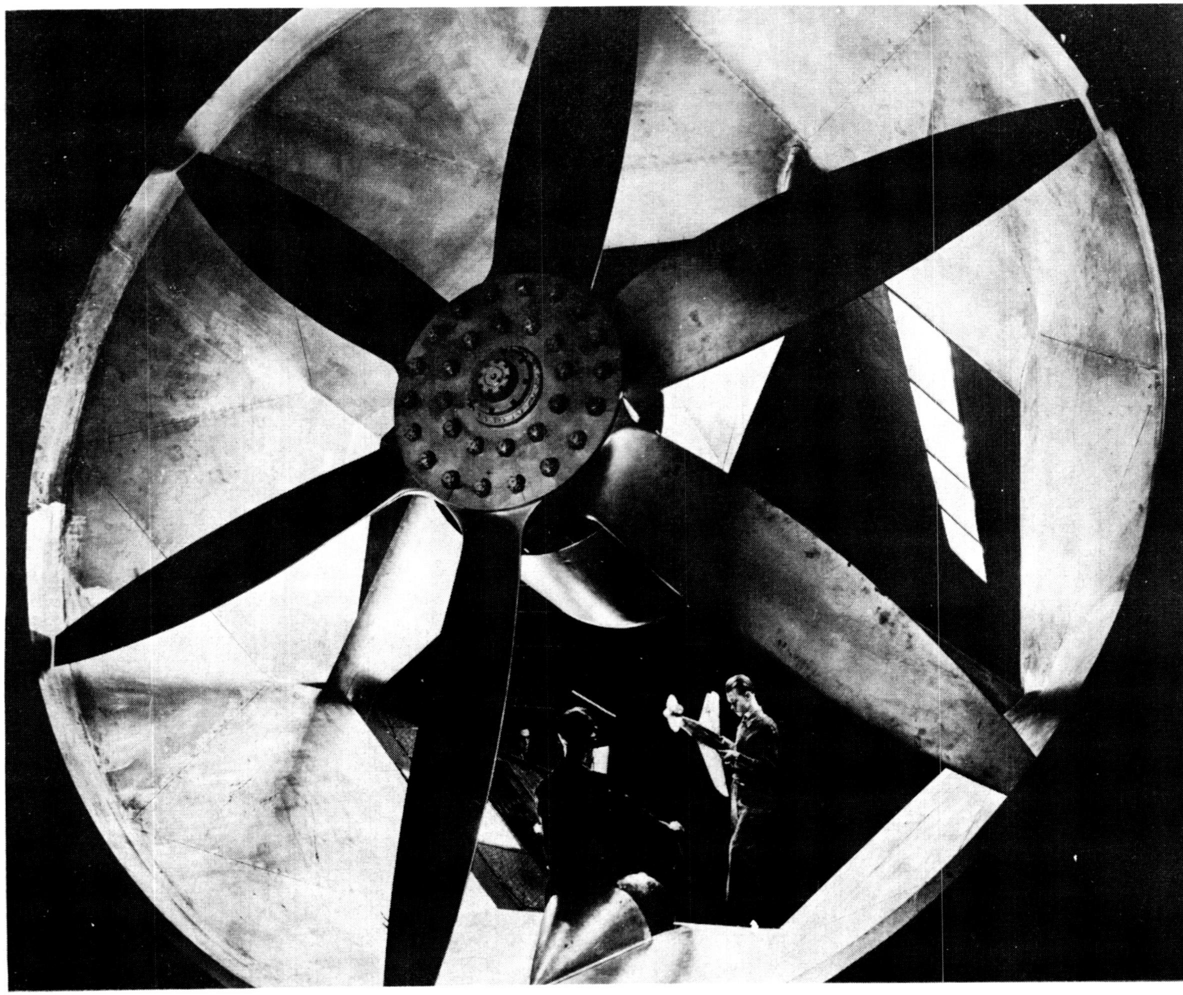

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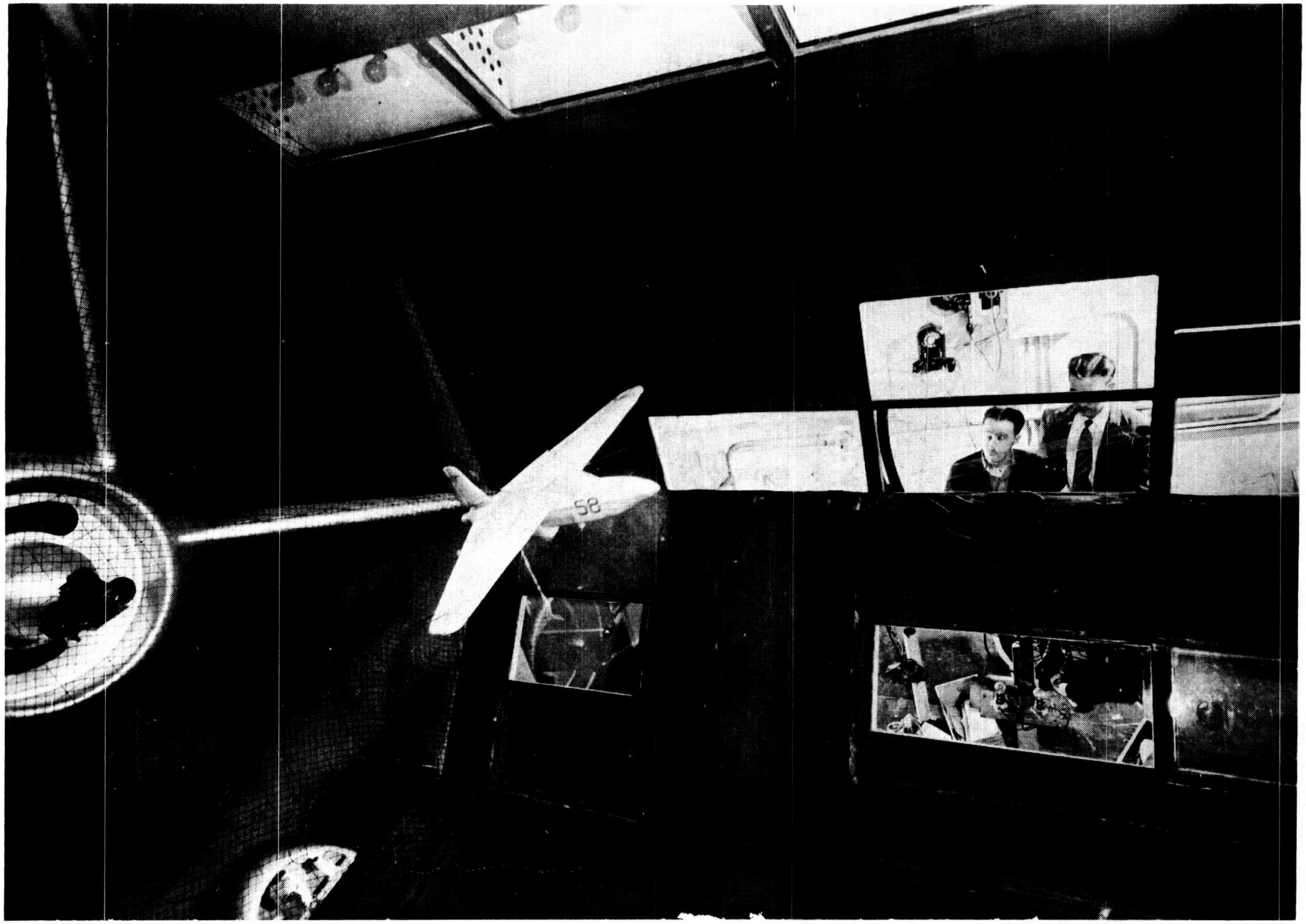
Figure 6.- Model being prepared for flight in 12-Foot Free-Flight Tunnel.



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L-46902

Figure 7.- Model in flight in 12-Foot Free-Flight Tunnel.

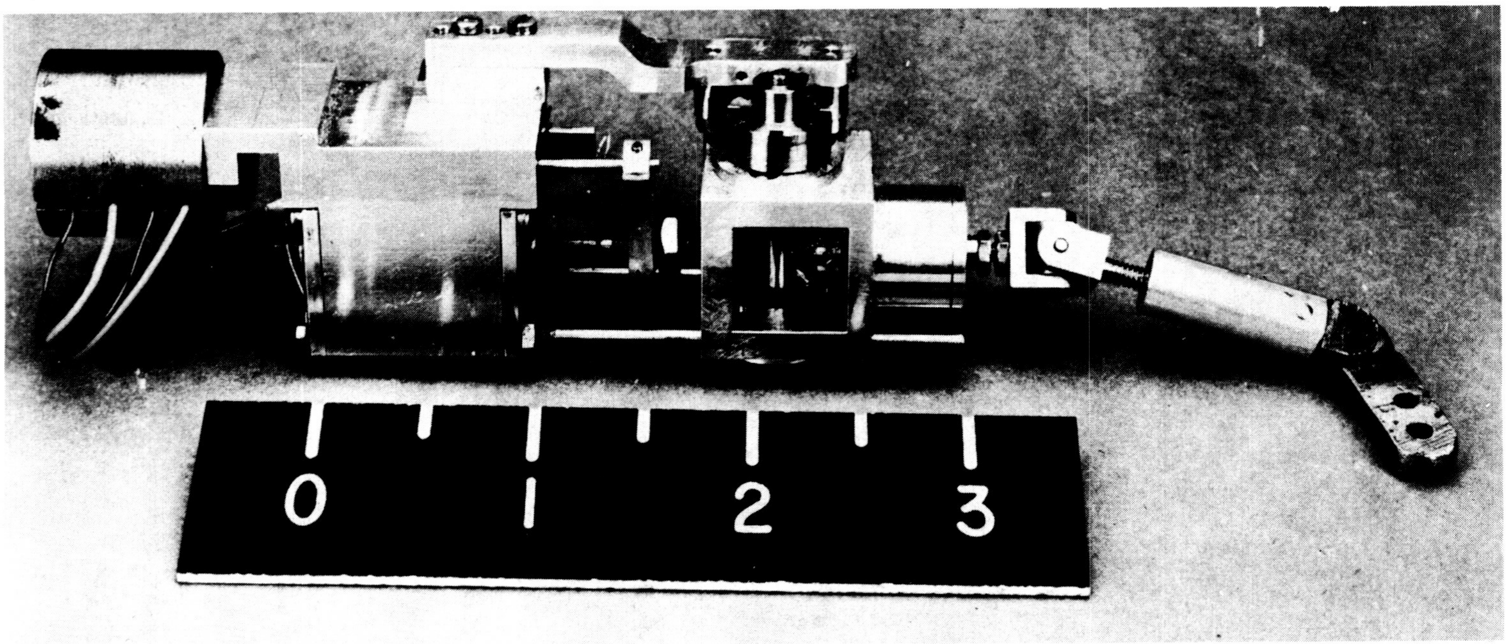

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Figure 8.- Pneumatic control actuator of the "bang-bang" or "flicker" type used in model flight testing by the NASA at Langley Research Center.

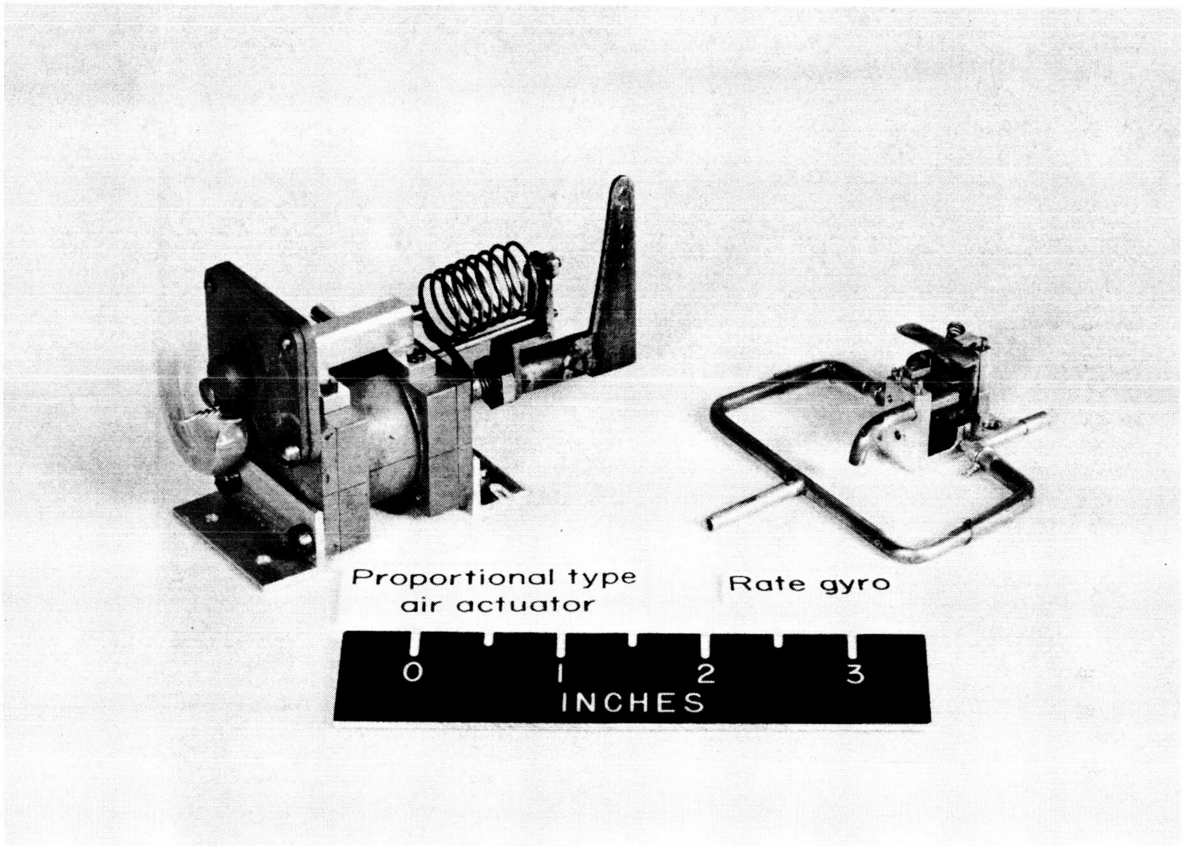

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Figure 9.- Proportional control actuator and rate gyro used in artificial stabilizing devices in flying models tested at the NASA Langley Research Center.

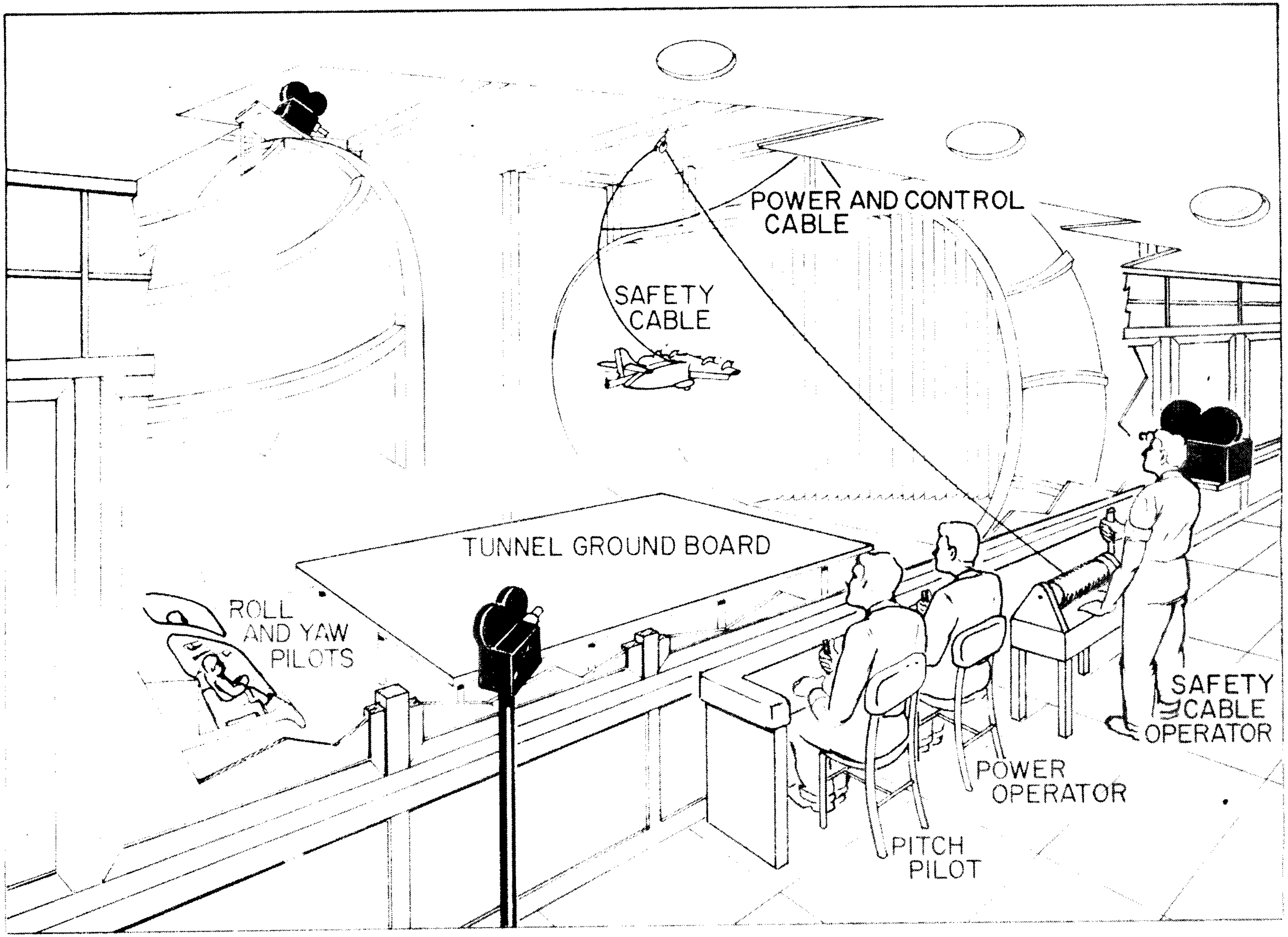

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Figure 10.- Test setup for free-flight model testing in NASA Langley Full-Scale Tunnel.

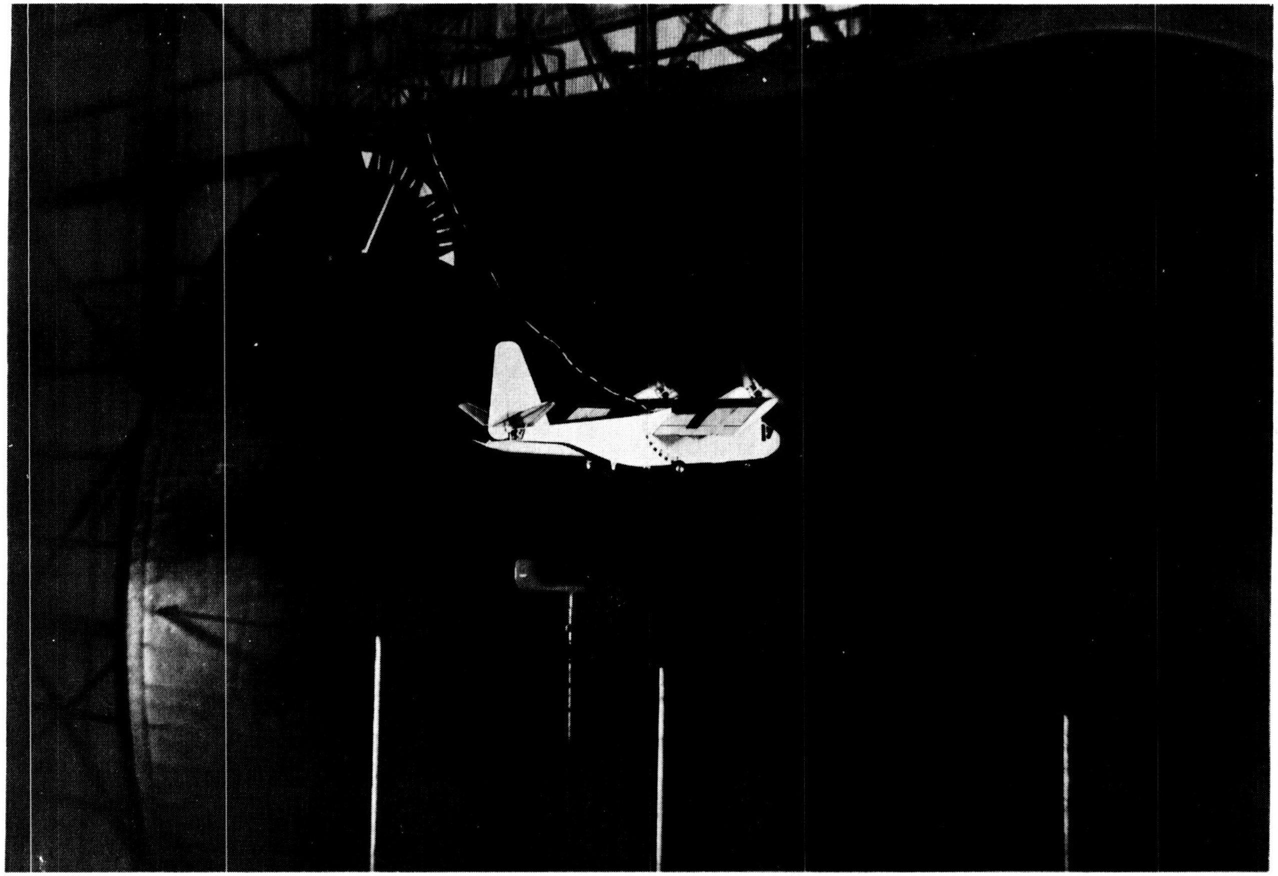

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Figure 11.- VTOL model in transition flight in NASA Langley Full-Scale Tunnel.

NASA
L-61-424

Figure 12.- Model of propeller-powered parawing utility model in flight in the NASA Langley Full-Scale Tunnel.

NASA
L-62-6318

Figure 13.- Model of XC-142 Tri-Service V/STOL airplane used in flight testing by the NASA.

NASA
L-59-8482

Figure 14.- Radio-controlled model installed on special helicopter launching rig in tests conducted by NASA Langley Research Center.

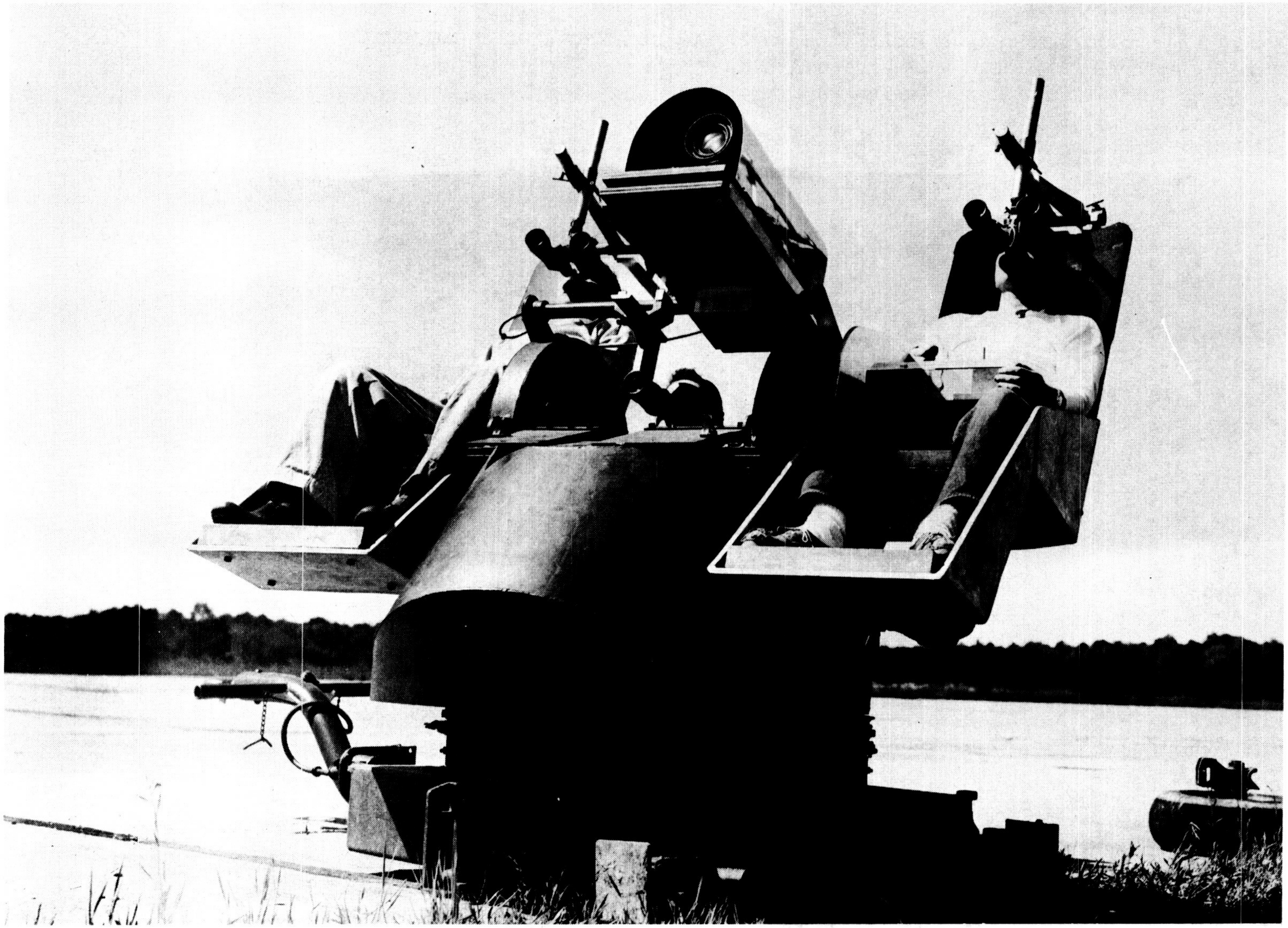

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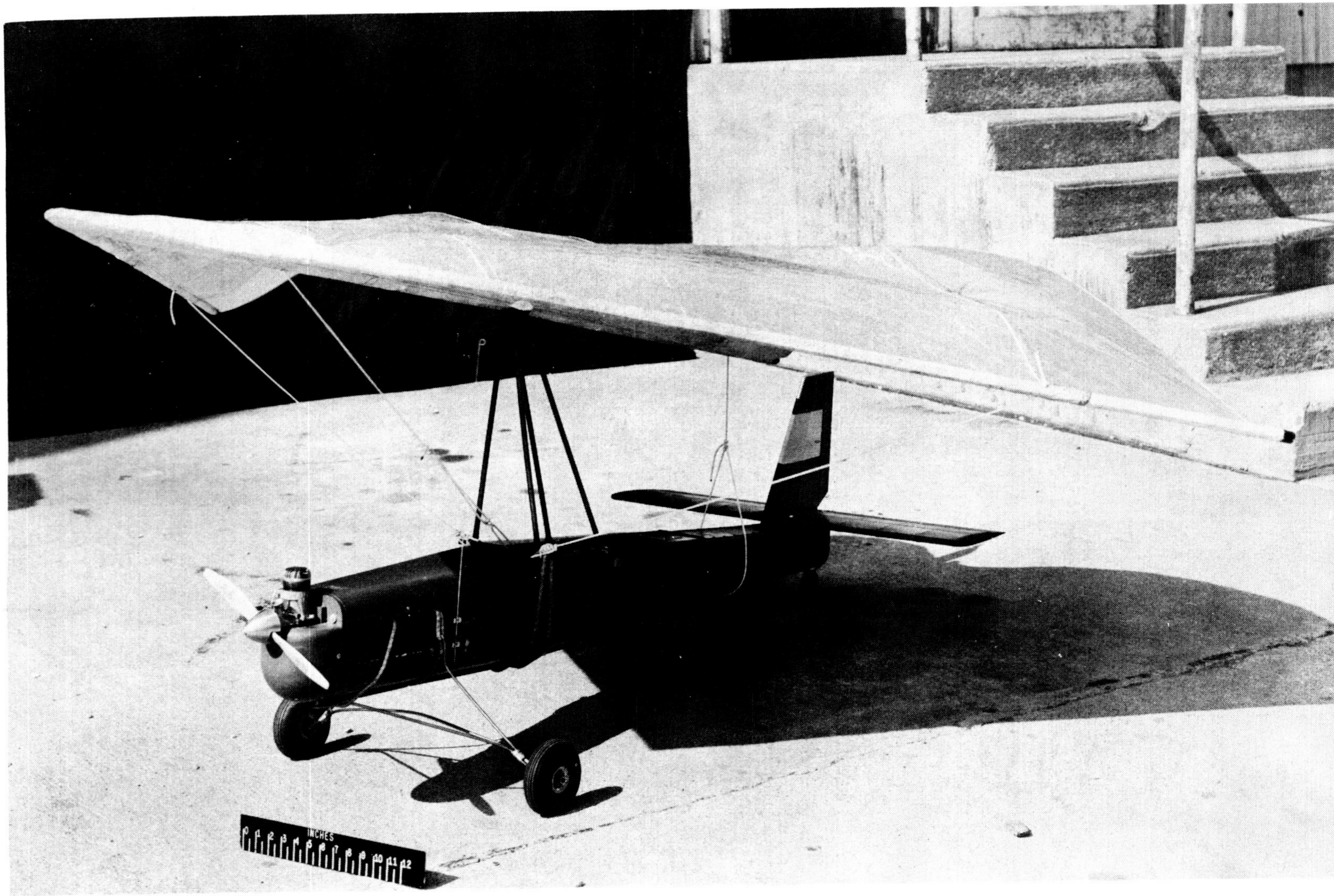
Figure 15.- Tracking unit used as ground control station in NASA research with radio-controlled models.



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L-60-3017

Figure 16.- Radio-controlled model equipped with parawing used in NASA research.

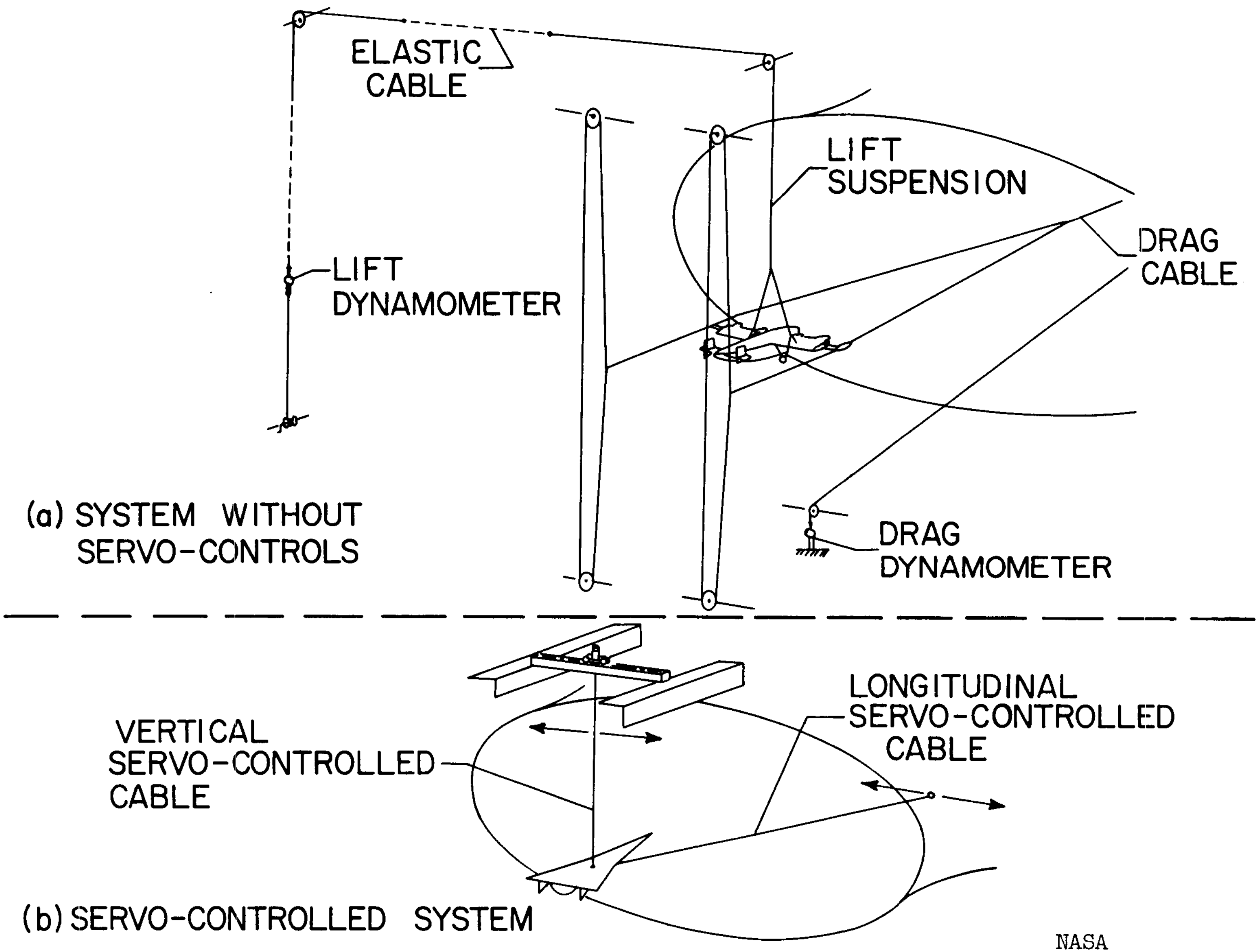
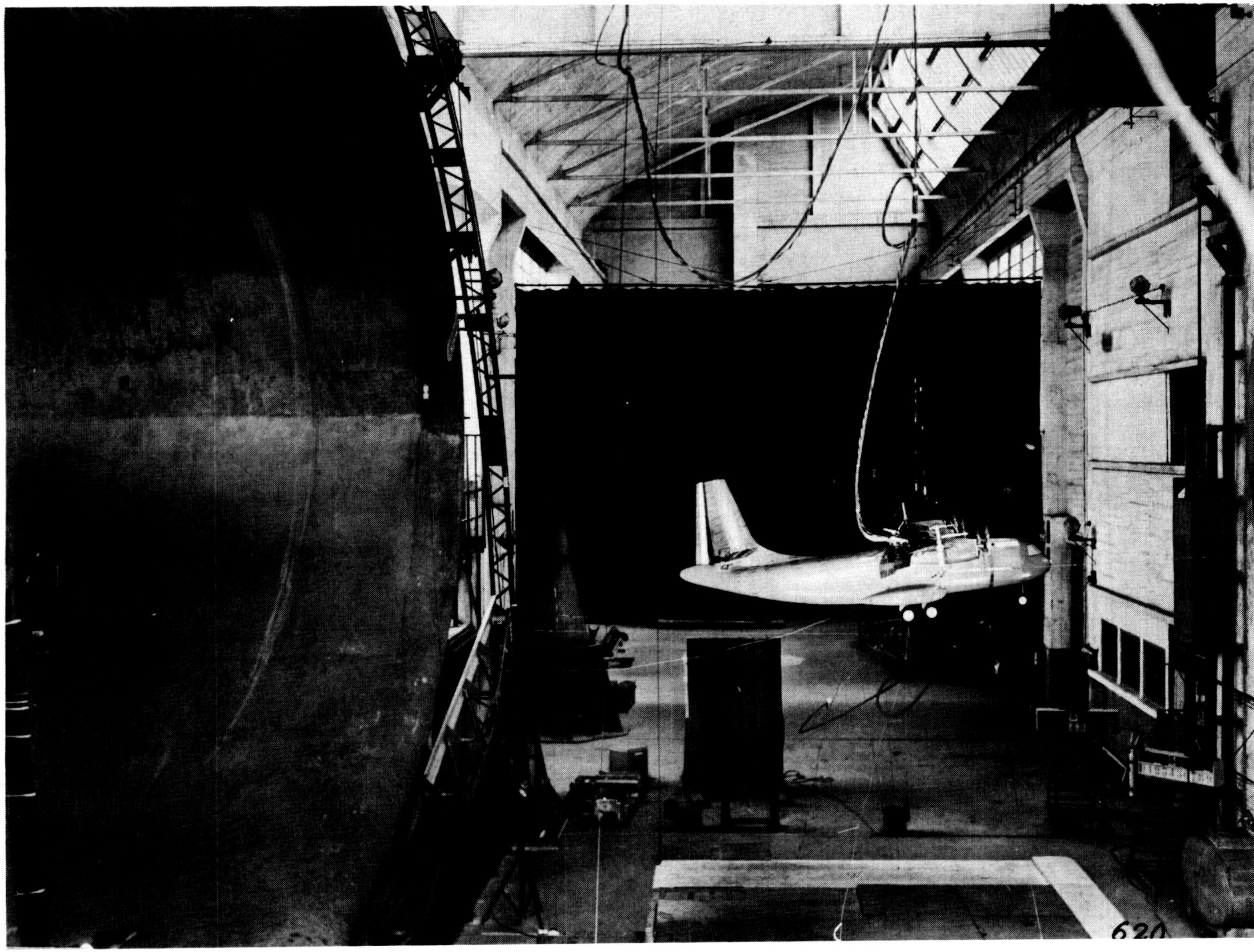


Figure 17.- Diagrammatic sketches of funicular suspension systems used by ONERA in semifree flight testing in the large S1Ch wind tunnel at Chalais-Meudon.



NASA

Figure 18.- Model in semifree flight in the large S1Ch wind tunnel at Chalais-Meudon.

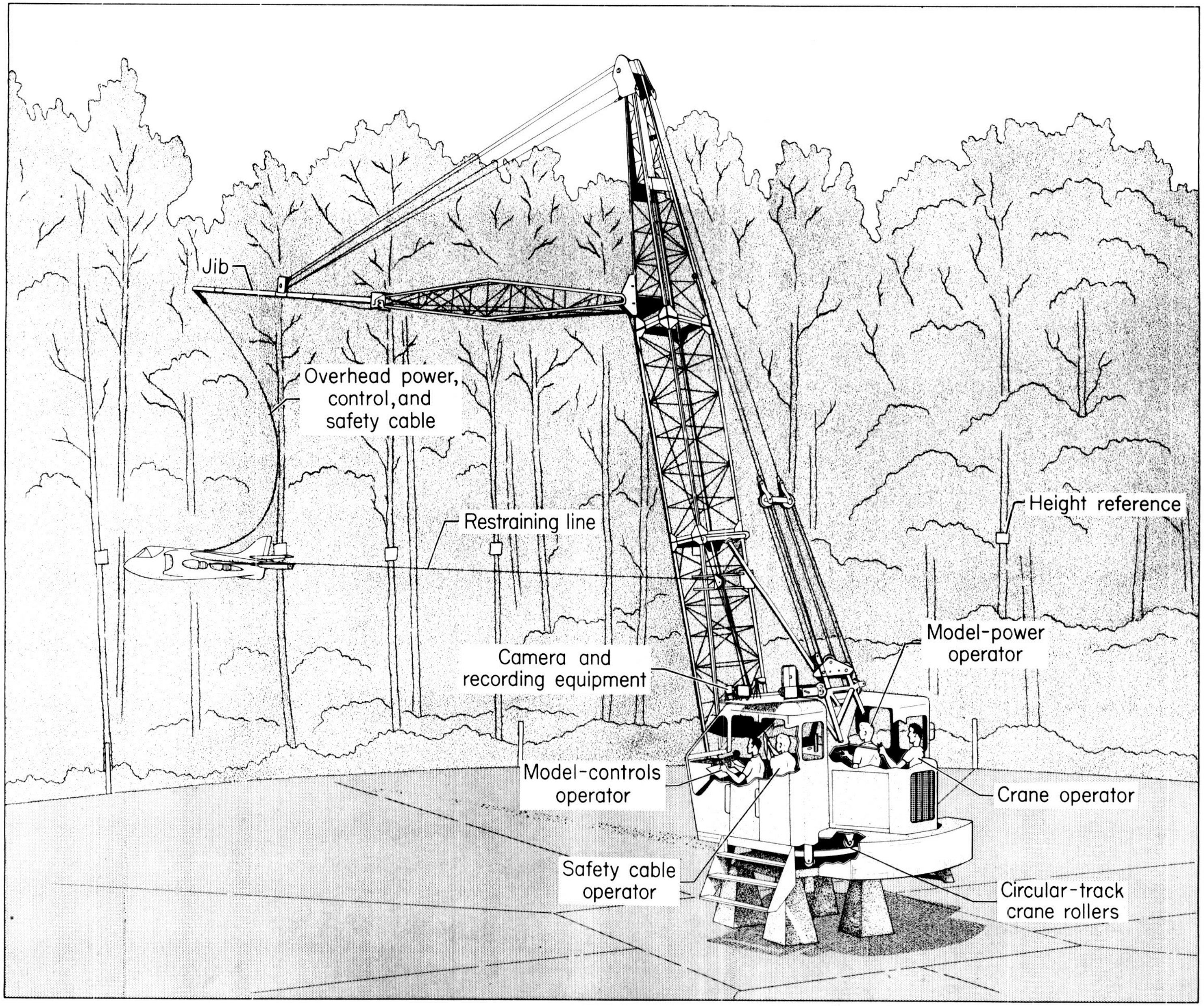


Figure 19.- The NASA Langley Control-Line Facility. NASA

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L-94283

(a) Hovering flight.

Figure 20.- Model powered with hydrogen-peroxide rocket motor in flight on the Langley Control-Line Facility.

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(b) Transition flight.

Figure 20.- Concluded.

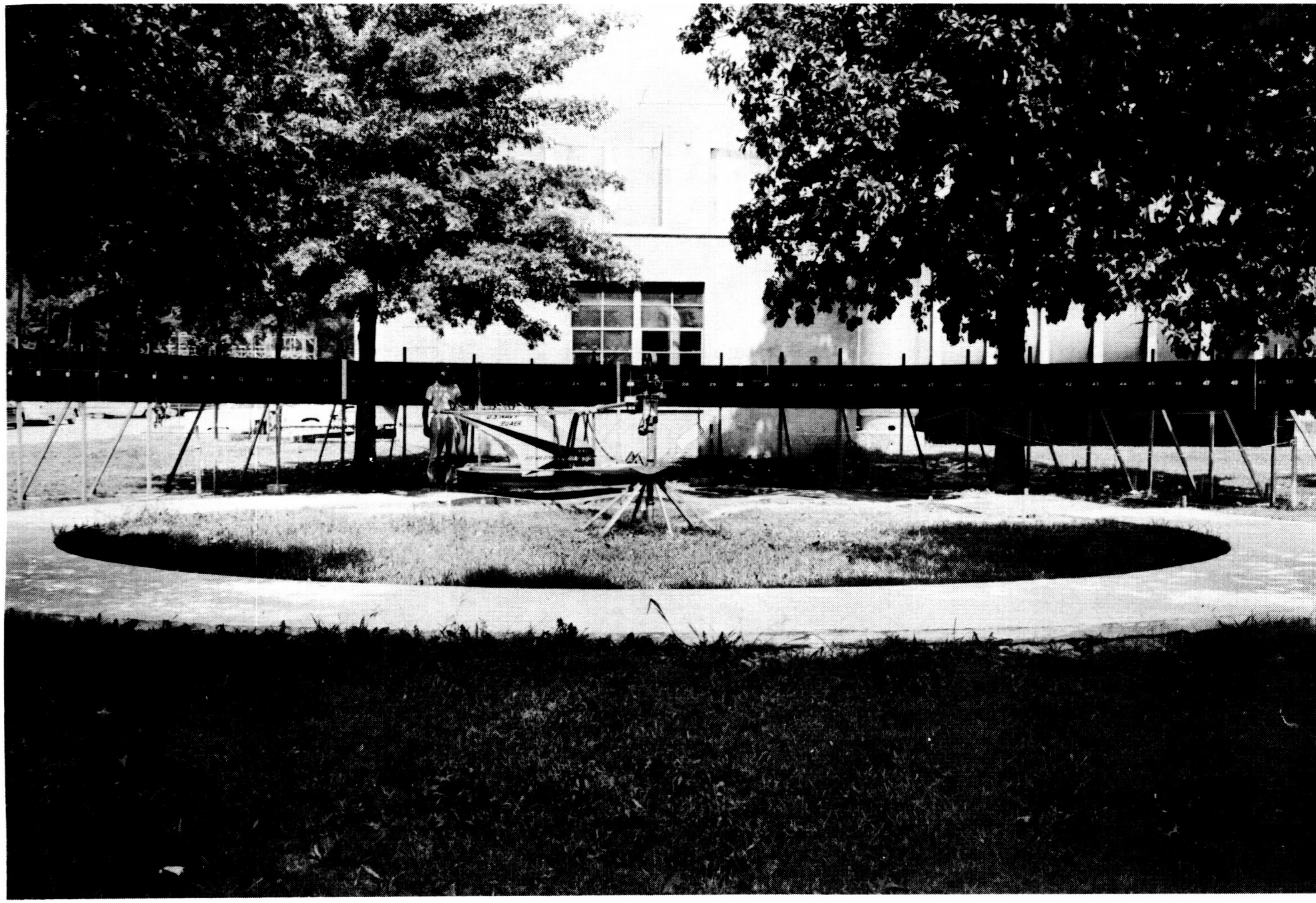

Figure 21.- Circular test track used for dynamic stability and response tests on ground-effect machines at David Taylor Model Basin.

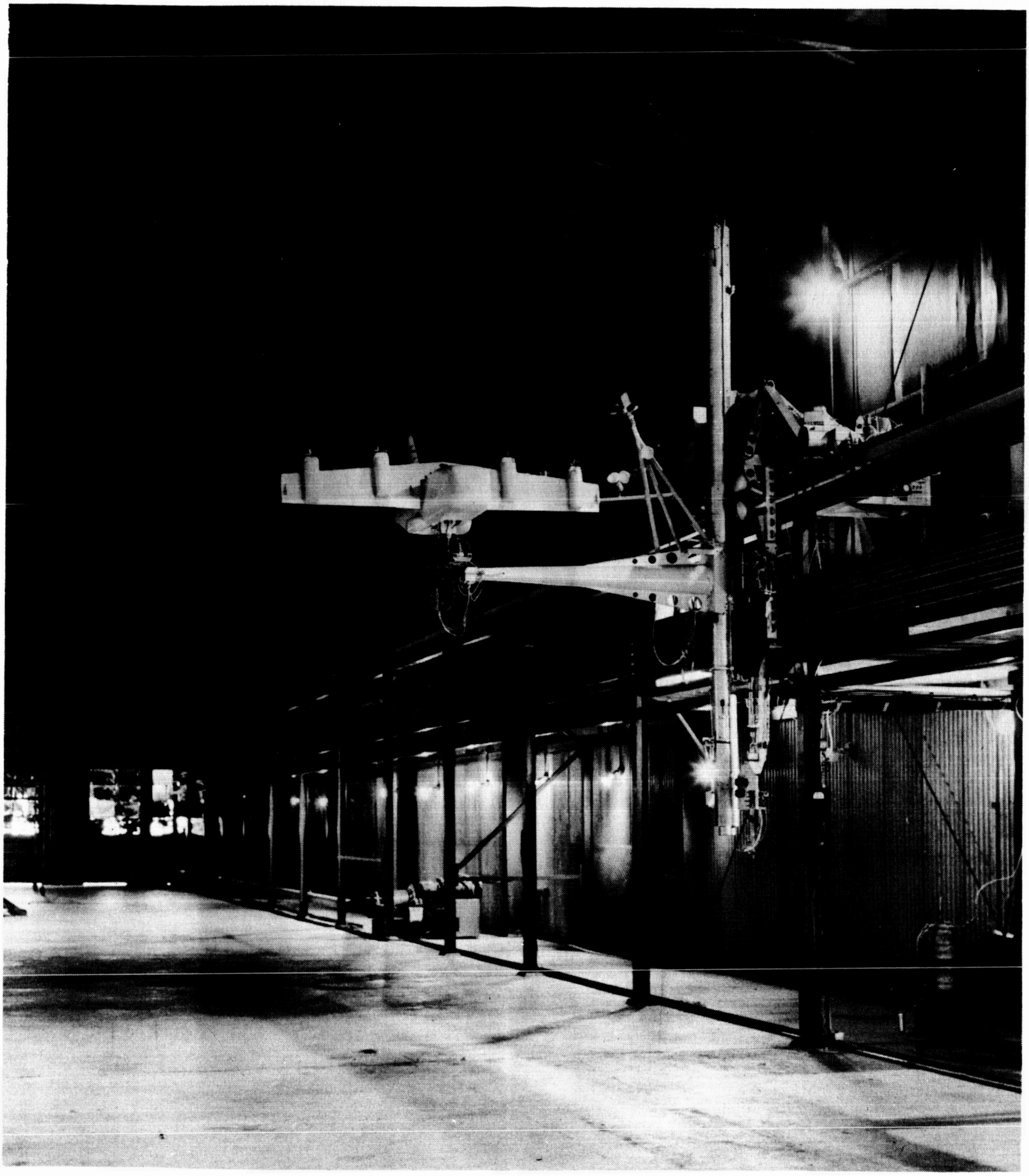

Figure 22.- Princeton University Forward-Flight Facility used for semi-free flight tests of V/STOL aircraft models.

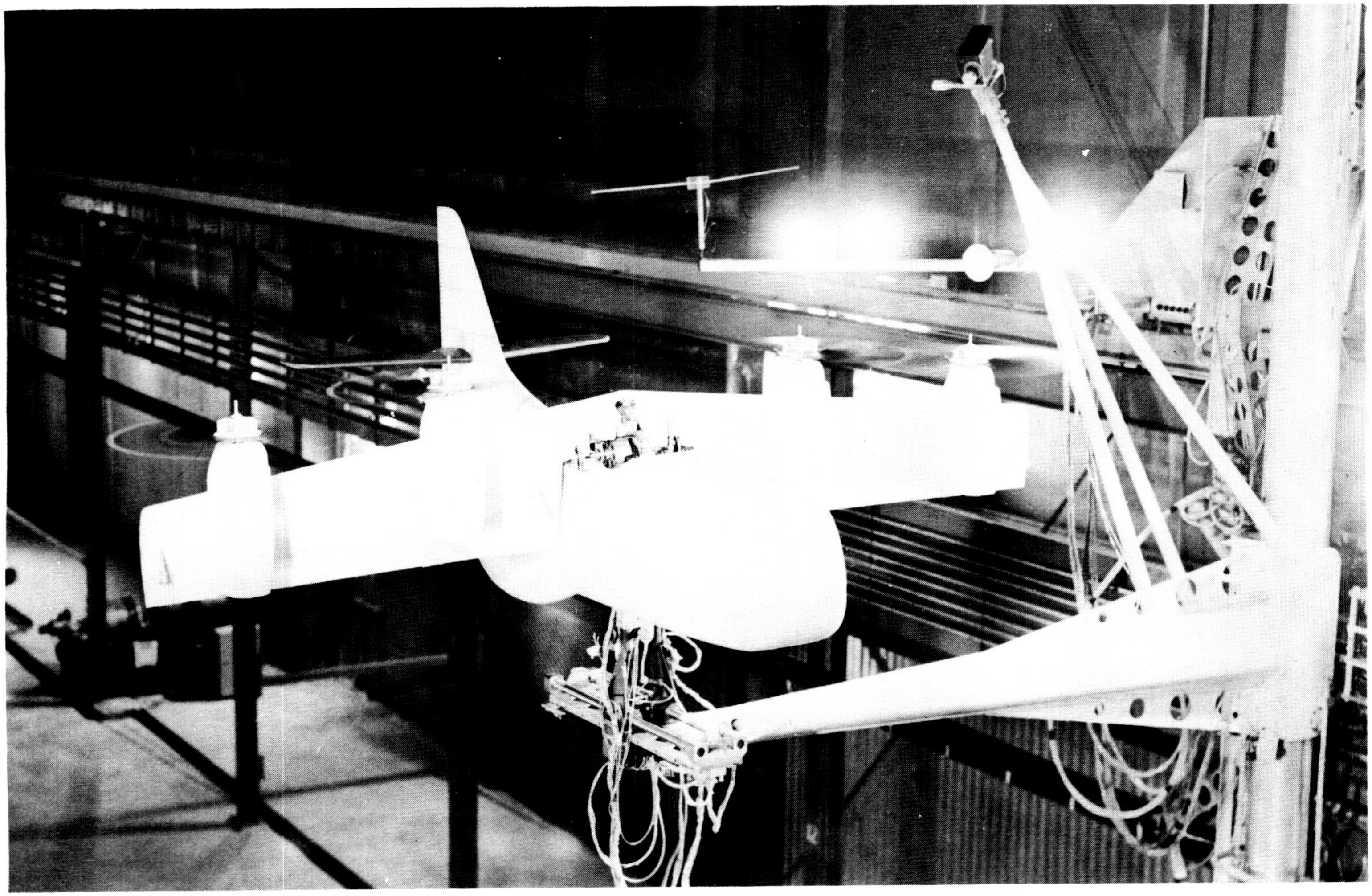

Figure 23.- Tilt-wing V/STOL model mounted for testing on Princeton University Forward-Flight Facility.

NASA-Langley, 1963